Environmental Policies That Shape Productivity: Evidence from Cattle Ranching in the Amazon

Fanny Moffette, Marin Skidmore and Holly K. Gibbs*

October 28, 2019

Abstract:
We examine potential economic benefits of environmental policies, increased agricultural investment and productivity. Two anti-deforestation policies in the Brazilian Amazon are analyzed: the Priority List, which increases the intensity of fines for deforestation, and the G4 Cattle Agreements, which is a market exclusion mechanism. We compare cattle ranchers' optimal behavior under each policy and extract predictions about their impacts in order to determine which agricultural actors are affected and what the expected combined policy effects might be. A spatial database that covers land-use in Brazil from 2004 - 16 combined with a unique dataset of slaughterhouse locations provide sample comparability since we restrict our analysis to municipalities that ever had an exporting slaughterhouse nearby. We use variations in time and exposure levels of the two policies and find that both increased productivity, while the G4 also increased investment. This research reveals both indirect and unexpected benefits of environmental regulation.

Keywords: Environmental regulation, unexpected benefits, Brazil, Amazon, cattle, productivity, land investment, induced intensification.

*Moffette: Nelson Institute for Environmental Studies and Department of Agricultural and Applied Economics, University of Wisconsin-Madison. Skidmore: Department of Agricultural and Applied Economics, University of Wisconsin-Madison. Gibbs: Department of Geography, Nelson Institute for Environmental Studies, Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison. We thank Jennifer Alix-Garcia, Jens Engelmann, Jeremy Foltz, Laura Schechter, and participants at the MWIEDC 2019, AERE Summer Conference 2019, Development Workshop at the University of Wisconsin-Madison for helpful comments and suggestions. Jacob Munger assisted with the construction of the panel database and Ian Schelly prepared the maps. Funding provided by the Gordon and Betty Moore Foundation and Norwegian Agency for Development Cooperation's Department for Civil Society under the Norwegian Forest and Climate Initiative. Any errors or omissions are the sole responsibility of the authors.

1 Introduction

The literature on environmental regulations has traditionally focused on measuring their effect on emissions, but a growing body of research analyzes their indirect economic benefits. Through change in input usage or health, environmental regulation can increase productivity and alter the labor supply, social capital, and R&D.[1] Despite the potential impact on productivity and investment, little attention has been paid to indirect benefits of policies to protect forest. By making land artificially scarce and unavailable for conversion to agriculture, environmental policies can have positive spillovers onto productivity. When land is relatively inexpensive and widely available compared to capital, agricultural producers should expand their production rather than intensify it; producers typically do not adopt semi-intensive methods until land clearing is no longer an option (Angelsen, 2010; Kaimowitz and Angelsen, 2008; Phalan et al., 2016). By using the case of skyrocketing cattle production in the Brazilian Amazon, we theoretically and empirically examine the impacts of two environmental policies on productivity and investment in inputs and capital. Specifically, we study the Priority List (*Municípios Prioritários*), which began in 2008 and sought to increase the expense of deforestation fines in targeted municipalities, and the G4 Cattle Agreement (G4), which began in 2010 and is a zero deforestation agreement that excludes suppliers with post-2010 deforestation.

The cattle herd in the Brazilian Amazon has grown by 270% from 23 million head in 1988 to 85 million head in 2016 (IBGE, 2017), making Brazil the world's leading producer and exporter of beef (USDA Foreign Agricultural Service, 2019). Despite this increase, production in the region is characterized by extensive ranching that produces only a third of the animals that could be supported on the same pasture area under methods of sustainable intensification (Ermgassen et al., 2018; Gil et al., 2018). Whether increases in agricultural productivity would decrease deforestation has been widely debated in the economic and environmental literature and remains a fundamentally empirical question.[2] In Brazil, studies suggest that productivity increases can lead to decreased deforestation (Assunção et al., 2015, 2017; Cohn et al., 2014). This is of crucial importance for the Amazon because low-density cattle production has been widely associated with high deforestation rates (Nepstad et al., 2014) characterized

[1] Agricultural productivity can be improved by mining regulations (Aragón and Rud, 2016) and anti-deforestation policies (Koch et al., 2019); labor productivity (Archsmith et al., 2018; Hanna and Oliva, 2015) and firm productivity (Berman and Bui, 2001; Yang et al., 2012) can increase through changes in air quality. Payments for environmental services programs support social capital (Alix-Garcia et al., 2018) and stringent air quality regulation increases R&D (Yang et al., 2012).

[2] On the one hand, Borlaug's hypothesis (following Borlaug 2007) states that increased productivity allows producers to increase production without additional land, and thereby reduces clearing. On the other hand, Jevon's paradox states that productivity increases clearing by increasing the profitability of land. If Jevon's paradox is true, increases in productivity caused by a response to environmental policies could lead to no aggregate impact on deforestation. See Villoria et al. (2014) for a review.

by 788,000 km^2 of forest loss through 2018 (INPE, 2019). A combination of public and private policies has successfully reduced deforestation since 2004 (Burgess et al., 2018; Assunção et al., 2019), but analysis of their effects on productivity and investment is sparse.

Our research provides a first attempt to examine how, in theory, private- and public-led environmental policies could complement one another to reduce deforestation and increase productivity.[3] Our two-period model with pasture degradation predicts ranchers' input usage, clearing and productivity decisions under a fines-for-deforestation policy (i.e. the Priority List), a supply chain exclusion policy (i.e. the G4), and a combination of the two. By increasing the expected penalty for larger areas of deforestation, the Priority List should have greater effects on large ranches with substantial remaining forest. By penalizing any deforestation, the G4 should separate ranchers into those who simply intensify and those who continues to deforest. Thus each policy is potentially more effective in some contexts than in others and our work seeks to predict the expected combined effects of the two.

We study the policies empirically using a sample of municipalities in the Amazon biome that have ever been influenced by one or both. A unique spatial dataset that identifies slaughterhouse location enables us to analyze only those municipalities that have ever had a G4-owned slaughterhouse[4] either in the municipality or within a 100-km buffer, and to the *Municípios Prioritários* (MPs) that are adjacent to this sample. This provides the advantage of using slaughterhouse location choices, which are based both on observables and unobservables, to ensure sample comparability. Our analysis also integrates an annual spatial dataset that identifies changes in pasture; this is used to normalize productivity (measured as cattle/ha of pasture) and investment (measured as credit for livestock/ha of pasture). Using a difference-in-differences strategy, we test the effect of the G4 and the Priority List, as well as their interaction.

Our results suggest that both policies increased productivity and that investment increased after exposure to the G4, although results were heterogeneous across municipalities. Those that were exposed only to the G4 increased their productivity by 6.10% compared to their baseline level, while municipalities that were exposed only to the Priority List saw an increase of 11.54%. In accordance with the conclusions of our micromodel, municipalities that were exposed to both policies saw the largest effect, with an increase of 16.36%. We also show that the G4 increased investment in inputs and capital specific to livestock by at least 5.35 billion reais in combination with an additional 81,556 credit contracts. Productivity increased more in municipalities with less remaining forest (as ranchers had less to gain from

[3]While other authors such as Azevedo et al. (2017); Heilmayr and Lambin (2016); Heilmayr et al. (2019); Lambin et al. (2014); le Polain de Waroux et al. (2019); Nepstad et al. (2014) study the importance of private- and public-led environmental policies, none developed theoretical analysis.

[4]G4-owned slaughterhouses refer to plants owned by one of the four largest meatpacking companies in Brazil, who are the only signatories of the G4 Cattle Agreements (see section 2 for more details).

breaking the zero-deforestation policy) and in municipalities closer to G4 slaughterhouses (as ranchers faced the strongest potential loss if they were excluded from the supply chain following deforestation). The Priority List largely had an effect in municipalities with high proportions of large ranches, since these ranches faced higher risk of being fined should they deforest.

To complement our analyses and to address endogeneity concerns, we carry out several robustness as well as falsification tests. First, since the causality of our estimates depends on the parallel trend assumption, we test and find supportive pre-trends. Next, we support with falsification tests the premise that the results were driven by the G4 rather than by the presence of a major slaughterhouse by using an alternative sample that includes all municipalities that had a G4-owned slaughterhouse (either in the municipality or within a 100-km buffer), but that are outside the Amazon. Third, to avoid bias that could enter our estimates from changes in slaughterhouse and supplier locations, we test the robustness of our results by limiting our analysis to 2004 - 12. Fourth, we show that our results are robust if we exclude the municipalities that were MPs but were never within the reach of the G4. Finally, our empirical strategy supports previous evidence of reduced deforestation by the Priority List and no evidence of reduced deforestation induced by the G4.

Studies on the Priority List have shown that the policy was effective (Arima et al., 2014; Cisneros et al., 2015; Assunção and Rocha, 2014; Assunção et al., 2019). Early analysis by Assunção and Rocha (2014) found that deforestation would have been 54% higher without the policy. Cisneros et al. (2015) demonstrate that the policy had a stronger effect during its second year, and the reduction in deforestation was strongest in the third year after addition to the list. A novel analysis by Assunção et al. (2019) confirmed that the policy's reduced deforestation between 2008 - 19 and further identified a set of targeted ex-post optimal municipalities for the list; this list would result in 7.4% lower carbon emissions than the actual list of municipalities, and 25% lower carbon emissions than a list of randomly chosen municipalities. Koch et al. (2019), the first authors to study the impact of anti-deforestation policies on other outcomes, estimate that the effect of the first list (2008) was not only to decrease deforestation, but also to increase cattle productivity.

In relation to this literature, our work adds three contributions. First, we study the impact of this policy on investment in inputs and capital. Next, we consider medium-run treatment effects by analyzing municipalities from all lists published before 2016 and observing effects up to eight years after a municipality was added to the list.[5] Finally, we extend the analysis of cattle productivity of Koch et al.

[5]Indeed, none of previous studies on the Priority List analyze the full scope of the policy. Arima et al. (2014); Cisneros et al. (2015); Assunção and Rocha (2014); Assunção et al. (2019) restrict data from one to four years after the beginning of the policy and analyze municipalities that were added to the list before 2012 and Koch et al. (2019) limit their treatment

(2019) by estimating a full panel from 2004 - 16 of productivity measures, compared to their analysis, which was limited to three years, with a single time-period after the policy began. Further, we expand their micromodel by considering pasture degradation (rather than credit constraints) as a mechanism through which the policies can affect productivity. Pasture degradation results from a lack of investment in the land and plays a critical role since it can eventually render the land unproductive and lead to deforestation.

The number of commitments to reduce deforestation in supply chains has greatly increased in recent years (Lambin et al., 2018; Garrett et al., 2019) and covers a wide range of commodities such as cattle, soy, cotton, cocoa, and palm oil. Some of these agreements reduced deforestation (e.g. Carlson et al. 2017), but none have been analyzed theoretically and robust empirical analysis remains limited. The G4, studied here, is a policy that was stimulated by an unexpected Greenpeace campaign that linked cattle to deforestation in the Brazilian Amazon. Overall, the G4 has been shown to modify purchase behavior of large meatpacking exporters (Gibbs et al., 2016, 2019) and to have heterogeneous effects on deforestation characterized by its decrease on certain properties and leakage of avoided deforestation on others (Alix-Garcia and Gibbs, 2017). This evidence suggests that the policy generated some effects, but their impacts were mitigated by avoidance behavior.

We contribute to this literature with the first theoretical model of producer decisions under a market exclusion policy (which defines under which circumstances it could lead to avoided deforestation). Given the remarkable expansion of these commitments, our model is important as it brings to light the expected consequences of this type of policy when enforcement is imperfect. We also estimate for the first time whether the G4 might have generated benefits other than an aggregate null effect on deforestation (i.e. effects on productivity and investment).

By studying policy interactions, this paper enriches the broad literature of environmental and development economics.[6] Governmental institutions often create policies that interact and can either substitute or complement each other. Understanding these interactions, which have clear consequences in terms of policy efficiency, is critical for improved design of environmental policies.

Finally, we contribute to the literature that investigates anti-deforestation policies. In the face of climate change, forest covers play a direct role as deforestation increases net carbon emissions. Consistent with our theoretical model, we show that ranchers substitute investment in inputs and capital, instead of

group to the original 36 municipalities on the 2008 list exclusively.

[6]Examples of the literature that studies policy interactions can be found in environmental economics (Sims and Alix-Garcia, 2017; Jaime et al., 2016) but also in other fields such as labor and health economics where these policy interactions are also frequent (Deserranno et al., 2019; Pless, 2019; Autor and Duggan, 2003; Inderbitzin et al., 2016; Ashraf et al., 2013).

deforesting, when they are subject to policies that penalize deforestation. We thereby provide evidence that efforts from the private sector could complement the public sector, especially in developing countries where the governments lack capacity to enforce laws or when laws are inadequate to protect forests.

2 Background

2.1 Cattle production in Brazil

Brazil's beef productivity is currently at one third of its sustainable potential. This extensive production of cattle in the Amazon is characterized by low investment in pasture, which over time has led to 40% of pasture being moderately or severely degraded (Ermgassen et al., 2018; Cohn et al., 2014; Strassburg et al., 2014). The degradation of pasture is partly explained by the high investment costs to restore or increase its productivity, although credit for livestock is available to cover operating and investment costs (see section 4.2 for more details). Through mixed legume pastures, pasture rotation, correction of soil imbalance, pasture fertilization, silvo-pastoral systems, or confinement operations, high productivity ranching requires $410 - 1,280 per ha in startup costs, and can take 2.5 - 8.5 years to repay its investment. Specific initiatives to introduce these techniques have shown an increase in productivity from less than one animal unit per hectare to one and a half to three animal units per hectare (Ermgassen et al., 2018).

The typical production cycle of the cattle supply chain is complex. In the Amazon, ranches may specialize in raising calves, in intermediate fattening, or in the final fattening immediately preceding slaughter. Thus, animals may be transported among several properties before slaughter, which hampers the ability of slaughter and meatpacking companies to monitor their movement.

2.2 G4 Cattle Agreements

Following a Greenpeace-led campaign that linked deforestation to the cattle sector in Brazil, the four largest slaughter and meatpacking companies (JBS, Marfrig, Minerva and Bertin[7]) signed the G4 in October 2009. By threatening the reputation of brands that were buying meat from the Amazon, the NGO provided incentives for the slaughterhouses to sign these agreements, lest they lose exports and a portion of their domestic markets. For this reason, the companies agreed to exclude suppliers who deforested after 2009, who were accused of slave labor violations, who lacked environmental property

[7] Bertin was later acquired by JBS.

boundary registration, who were located within protected areas, or who had been embargoed (a tool by which the Brazilian Forest Code was applied and fines for illegal deforestation were imposed) (Greenpeace, 2009).

Since 2010, the G4 companies have been using the services of an agribusiness intelligence firm to determine the compliance status of their direct suppliers.[8] To evaluate compliance, the monitoring company first determines the suppliers' property boundaries. The property area is compared to geospatial data, and each supplier's tax identification number is compared to embargo and forced-labor lists. When a supplier is verified as compliant, the slaughterhouse proceeds with the sale. Thus, rather than tracking movements among properties throughout an animal's life, the slaughterhouses monitor only their direct suppliers. It is therefore possible for non-compliant cattle to enter the supply chains indirectly through intermediary suppliers. Such suppliers use this logistical loophole to launder cattle, or to move them strategically among properties for monetary gains (Walker et al., 2013; Gibbs et al., 2019).[9]

Research has shown that JBS, the world's largest meatpacking company, blocked non-compliant suppliers in some regions although in other regions enforcement was weaker, especially where competition from non-monitoring slaughterhouses threatened the company's quotas (Gibbs et al., 2016, 2019). As a consequence of incomplete enforcement and the laundering behavior of suppliers, deforestation decreased on properties with official boundaries but this decrease was undermined by an increase in deforestation on properties without official boundaries, and therefore, the G4 did not lead to net avoided deforestation (Alix-Garcia and Gibbs, 2017).

2.3 Priority List

In 2007, the President of Brazil signed a decree that permitted targeting and differential enforcement of environmental policies in municipalities with the highest incidence of deforestation. The Priority List was part of the action plan to curb deforestation (Portuguese acronym, PPCDAm). The first list was published in 2008 and included 36 priority municipalities (MPs) that were responsible for 45% of deforestation in 2007 (Assunção et al., 2013). Municipalities were then added and removed from the list in 2009, 2010, 2011, 2012, 2013, and 2017.

[8]Legally binding "Terms of Adjustment of Conduct" (TAC) contracts occurred on a similar timeline and obliged signatories to exclude suppliers linked to areas with illegal deforestation or violations of other government sanctions. While the major G4 companies monitored their suppliers since the beginning and signed both the G4 and the TAC, the slaughterhouses that only signed TAC did not monitor geospatial characteristics of suppliers (e.g. deforestation) until after the timeframe of this study (Gibbs et al., 2019).

[9]Recent negotiation to monitor the G4 proposed tracking of animals through the Guide to Animal Transport (GTA), documents issued by state-level sanitation control agencies for all transport of cattle. The GTA include the origin and destination of the cattle being moved, but no formal agreement has yet been reached.

The creation of the Priority List gave the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) the power to dedicate a larger share of their resources to MPs (Assunção et al., 2013). IBAMA is responsible for monitoring changes in land cover in the Amazon using the Real-Time Detection of Deforestation System (DETER). After receiving alerts, IBAMA issues fines and embargoes properties. The Priority List authorized IBAMA to prioritize alerts in MPs, and thus properties in MPs were at higher risk for environmental fines or embargoes. Other Amazon-wide environmental policies were to be strictly enforced in MPs, including Resolution 3.545, which requires that banks deny credit to properties that are not in compliance with environmental law (Presidéncia da República, 2009). This portion of the policy has been shown to have been less effective than the command and control enforcement implemented by IBAMA (Assunção et al., 2013; Cisneros et al., 2015).

Officially, municipalities were chosen based on their total deforested area, recently deforested area, and recent rate of change in deforestation. However, Assunção et al. (2019) show that while the level of previous deforestation was a strict criterion, the recent rate of change of deforestation did not influence placement on the list. These authors show that assignment to the list was determined by official criteria and was not influenced by political factors[10] and Pailler (2018) finds further evidence that local politicians have had little influence over environmental enforcement and fines.

3 A model of cattle ranching

We develop a basic model for a cattle rancher's choice of pasture area and inputs and then we introduce two policies: one uses fines-for-deforestation and the other consists of market exclusion following clearing. We compare the optimal levels of key factors under each policy to the basic model. To gain further insights, we consider the case where both policies are enforced. We conclude by presenting testable hypotheses.

We model the same decision choice as Koch et al. (2019): whether to expand pasture area or invest in inputs. Our model departs from theirs in several meaningful ways. First, we model two distinct policies that decrease the benefit of clearing pasture, one of which is dependent on production quantity and another that is independent. Next, we do not impose a credit constraint. While many ranchers in the Amazon indeed experience credit constraint (Assunção et al., 2013), this assumption limits the model's ability to draw conclusions about large unconstrained landholders who are also likely to make critical

[10] Assunção et al. (2019) were able to replicate 97% of the 2008 list using inferred thresholds for the total deforested and recently deforested areas. They find common trends in deforestation among the municipalities on either side of this threshold, which lends support to the statement that assignment was not based on political influence.

decisions about productivity and clearing. Also, the inclusion of an exogenous credit constraint could be inappropriate given the Priority List's potential direct impact on credit availability. Finally, we consider the reality of pasture degradation. While cleared land may gain speculative value over time (Vale, 2015), it loses productive capacity as pasture becomes degraded, typically within a decade for Amazonian soils (Fearnside and Barbosa, 1998). Similarly, in the Brazilian state of Rondônia, twelve-year-old pasture was found to be half as productive as three-year-old pasture (Fearnside, 1989). By incorporating this essential factor, our model depicts a reality faced by ranchers who are choosing between land and investment in inputs and capital for production.

3.1 Theoretical model setup

With a two-period model, we represent rancher decisions to produce cattle using pasture and a set of inputs. Cleared pasture is represented by H and incurs a per unit cost c. Pasture degrades in the second period by $(1-\alpha)$ percent, where $0 < \alpha < 1$. Since we assume that land rental is not a viable option,[11] ranchers are constrained such that H cannot exceed their total area, A. Inputs M are used to increase the carrying capacity of land and can take two distinct forms: consumable inputs not transferable between periods (e.g., non-pasture feed, nutritional supplements, fertilizer) and capital that is transferable (e.g. tractors, machinery to reform pasture, or infrastructure for confinement and semi-confinement operations). The per unit cost of these inputs is r, which can be regarded as the cost of consumable inputs plus machinery rental or payments on loans for machinery or infrastructure.

We assume that within the two periods the size of the cattle herd is fixed. The rancher's objective is to produce "finished" animals that are at a desirable weight for slaughter. This requires that sufficient pasture or feed for the animals to gain weight is provided. Thus $f(H, M)$ is the production function of finished animals that are sent for slaughter, as the rancher does not earn income based on the size of their herd, but only on the number of animals sold.[12] We assume that $f(H, M)$ is concave in pasture and inputs, and that the two are substitutes. We normalize cattle prices to one.

[11]This assumption is largely representative of the land market in the Brazilian Amazon. In 2006, only 3.3% of Brazilian agricultural land was leased. By 2016, however, the proportion had increased to 8% nationally, but remained at 2% for the Northern region that encompasses the Amazon biome (IBGE, 2007, 2019)

[12]This definition addresses two objectives concerning animal acquisition as a method of increasing productivity. First, assuming that ranchers used pasture optimally in the past, to increase herd size requires additional pasture or inputs. Lacking this, the herd would become malnourished, and the rancher would risk losing animals to starvation, thereby undermining a short-term increase in productivity. Second, our main question of interest is not the acquisition of animals, but whether producers use intensive methods to raise them.

In the first period, ranchers maximize their profit subject to their land constraint:

$$\begin{gathered} Max_{\{H_1,M_1\}} \quad f(H_1,M_1) - rM_1 - cH_1 \\ s.t. \quad H_1 < A. \end{gathered} \tag{1}$$

The first order conditions (FOC) determine the levels of inputs and clearing, and by combining those, we find that the rancher produces where the ratio of the marginal revenues equals the ratio of the marginal costs, including the shadow cost of land tightness, λ:

$$\frac{\frac{\partial f(H_1,M_1)}{\partial H_1}}{\frac{\partial f(H_1,M_1)}{\partial M_1}} = \frac{c+\lambda}{r}. \tag{2}$$

In the second period, the rancher continues to produce on H_1, but this pasture degrades by $(1-\alpha)$ percent. For simplicity, we assume that inputs do not transfer between periods (representative of the consumable inputs case), but we detail a model with transfer of inputs in appendix A (representative of the capital transfer case) for which we find that all conclusions are consistent. Thus, the rancher maximizes in the second period:

$$\begin{gathered} Max_{\{H_2,M_2\}} \quad f((1-\alpha)H_1 + H_2,M_2) - rM_2 - cH_2 \\ s.t. \quad H_1 + H_2 < A. \end{gathered} \tag{3}$$

Pasture degradation requires that the rancher increase input use or clear additional pasture in the second period (H_2). The FOC for land requires:

$$\frac{\partial f((1-\alpha)H_1 + H_2, M_2)}{\partial H_2} = c + \lambda \tag{4}$$

and the FOC for inputs requires:

$$\frac{\partial f((1-\alpha)H_1 + H_2, M_2)}{\partial M_2} = r. \tag{5}$$

Assuming that c and r are unchanged, the FOC does not hold if $H_2 = 0$ and $M_2 = M_1$, and therefore the rancher must increase the use of either pasture or inputs, or both.

The rancher will continue to use the two in the ratio that satisfies the FOC:

$$\frac{\frac{\partial f((1-\alpha)H_1+H_2,M_2)}{\partial H_2}}{\frac{\partial f((1-\alpha)H_1+H_2,M_2)}{\partial M_2}} = \frac{c+\lambda}{r}. \tag{6}$$

In the next sections, we consider the effect of two policies on the rancher's second period decisions. We analyze changes in M (as this indicates the investment in inputs by ranchers), changes in H (as this shows whether ranchers are increasing or decreasing their stocking density), and changes in $\frac{M}{H}$ (which reveals the level of inputs ranchers choose per hectare).

3.2 Policy 1: Fines for deforestation

We model a policy where the government levies fines for clearing. The expected fine for cleared area H_2 is a function $P(H_2)$ increasing and convex.[13] This shape reflects the incomplete enforcement of fines. Larger areas of clearing not only incur higher fines but are also more likely to be noticed and prosecuted. If the rancher produces on H_1 and clear no additional pasture, $P(0) = 0$.

The maximization problem with the fines for deforestation becomes:

$$\begin{aligned} Max_{\{H_2,M_2\}} \quad & f((1-\alpha)H_1 + H_2,M_2) - rM_2 - cH_2 - P(H_2) \\ s.t. \quad & H_1 + H_2 < A \end{aligned} \tag{7}$$

and equation 6 now becomes:

$$\frac{\frac{\partial f((1-\alpha)H_1+H_2,M_2)}{\partial H_2}}{\frac{\partial f((1-\alpha)H_1+H_2,M_2)}{\partial M_2}} = \frac{c + \lambda + P'(H_2)}{r}. \tag{8}$$

The additional cost of clearing, $P'(H_2)$, results in a lower level of clearing than in the absence of the policy. Because pasture and inputs are substitutes, the marginal product of inputs increases when the level of clearing decreases. Therefore, M_2 is higher than in the absence of the policy and the ratio $\frac{M}{H}$ increases. It is interesting to note that intensification increases more for those properties with high optimal level of H_2 in the absence of policy, and this is due to the convex shape of $P(H_2)$. Ranchers have a larger response to the policy in the following cases:

1. When H_1 is high. Ranchers with larger areas of initial pasture requires more land to compensate for degradation.

2. When λ is low. Ranchers who are not land constrained choose H_2 with a relatively low marginal product of pasture. Because the production function is concave in pasture, the additional marginal

[13] The majority of properties in the Amazon biome are not in compliance with the Forest Code which allows clearing of only 20% of the property area (Godar et al., 2015). For example, 98% of the 26,510 direct suppliers of JBS in the Amazon are noncompliant (Gibbs et al., 2019). Thus, while deforestation can be legal, most of deforestation is not.

cost of pasture decreases the optimal level of clearing relative to a producer who is highly constrained.

3.3 Policy 2: Market exclusion following deforestation

We now examine a policy where a specific group of slaughterhouses refuse to buy cattle from recently cleared land; we refer to these slaughterhouses as the G4 slaughterhouses. When $H_2 > 0$, the rancher incurs a penalty β on the ranch's entire income. This penalty can take several forms, which include: (1) increased transportation cost to non-G4 slaughterhouses; (2) lower expected prices from non-G4 slaughterhouses; and (3) the cost of laundering cattle through compliant properties. If every slaughterhouse enforces the policy, then (1) and (2) are no longer an option, ranchers with non-compliant deforestation can sell cattle only through compliant properties (which pay less than the slaughterhouse price and keep β as profit margin). If market power concentrates on a few compliant properties, β should increase but remain lower than 1, since non-compliant properties would exit the market if the compliant properties extracted all the revenue. If no slaughterhouses would enforce the policy, $\beta = 0$.

The rancher now solves:

$$\begin{aligned} Max_{\{H_2,M_2\}} \quad & (1 - \mathbb{1}\{H_2 > 0\}\beta) f((1-\alpha)H_1 + H_2, M_2) - rM_2 - cH_2 \\ s.t. \quad & H_1 + H_2 < A. \end{aligned} \tag{9}$$

The ranchers maximize their profit without clearing (i.e., intensification) and with clearing (i.e. extensification) and choose the option that maximizes profit.

- **Case 1: Intensification (N)** ($H_2 = 0$)

  The rancher does not clear additional pasture (which fixes land at H_1) and solves:

$$Max_{K_2} \quad f((1-\alpha)H_1, M_2) - rM_2. \tag{10}$$

  In this case, the rancher maximizes based on one FOC:

$$\frac{\partial f((1-\alpha)H_1, M_2)}{\partial M_2} = r. \tag{11}$$

  Since inputs and pasture are substitutes and the rancher is setting $H_2 = 0$, M_2^N is higher than it would be in the absence of the policy. Thus, the ratio $\frac{M}{H}$ is higher than it would be in the absence of the policy.

- **Case 2: Extensification (X)** ($H_2 > 0$)

  Any rancher with clearing is subject to a penalty proportional to the quantity produced. The rancher maximizes:

$$\begin{aligned} Max_{\{H_2, M_2\}} \quad & (1-\beta)f((1-\alpha)H_1 + H_2, M_2) - rM_2 - cH_2 \\ s.t. \quad & H_1 + H_2 < A. \end{aligned} \tag{12}$$

  In this case, the ratio of the FOC is identical to equation 6, and the ratio $\frac{M}{H}$ is the same as it would be in the absence of the policy. Thus, no intensification occurs. However, the optimal levels of clearing and inputs, H_2^X and M_2^X, are lower than they would be in the absence of the policy because their marginal revenues decrease by β%.

Whether the rancher chooses intensification or extensification depends on which scenario yields greater profit. The rancher chooses intensification when:

$$f(H_1, M_2^N) - (1-\beta)f((1-\alpha)H_1 + H_2^X, M_2^X) > r(M_2^N - M_2^X) - c(H_2^X). \tag{13}$$

The terms on the left-hand side (LHS) represent the difference in revenue under the two scenarios. If H_2^X is very close to 0, the rancher loses revenue by deforesting because first, very little additional land is gained through deforesting, next, less input is used in response to the loss in revenue; and lastly, a penalty β is incurred proportional to production. Thus, the LHS is decreasing in H_2^X. On the right-hand side (RHS), M_2^N is always higher than M_2^X, as the rancher uses more inputs when intensifying. However, the rancher benefits by not paying a clearing cost $c(H_2^X)$ when intensification is chosen.

Thus, equation 13 will hold for small values of H_2^X, as the small area of additional land does not justify the $(1-\beta)$% loss of production. However, the rancher extensifies when H_2^X is high, as the production of $f((1-\alpha)H_1 + H_2^X, M_2^X)$ is sufficiently higher than $f((1-\alpha)H_1, M_2^N)$ to justify the loss of β% of revenue. This creates a point of discontinuity, $\tilde{H}_2$, such that for $H_2^X > \tilde{H}_2$ the rancher extensifies and produces at $f((1-\alpha)H_1 + H_2^X, M_2^X)$ and for $H_2^X < \tilde{H}_2$ the rancher intensifies and produces at $f((1-\alpha)H_1, M_2^N)$. Whether a rancher falls above or below this point of discontinuity depends on the particular value of $\tilde{H}_2$ (a function of β, c, r, and H_1) as well as the value of H_2^X (a function of λ, c, r, and H_1).

Ranchers are more likely to intensify in the following cases:

1. When the policy is strictly enforced and β is high.

2. When λ is high because of land tightness, leading to a low value of H_2^X.

3. When H_1 is low. We previously assumed that there are decreasing returns to inputs and the cross partial derivative of pasture and inputs is negative. Ranchers with smaller values of H_1 have a higher value of $\frac{f(H_1,M_1)}{M_1}$, which thereby allows them to adapt to a zero-deforestation setting more cost effectively by increasing input use, M_2 in the second period. We also assumed that degradation is linear in area. Thus, while both $\tilde{H}_2$ and H_2^X are increasing in H_1, $\tilde{H}_2$ is convex in H_1, while H_2^X is linear.[14]

In sum, the policy has the potential to create two sets of ranchers, one group who intensifies and invests in inputs and one who continues to produce at the same level of intensity as they would in the absence of the policy. The size of these groups is determined by context.

3.4 Comparison and interaction of the policies

3.4.1 Comparison of effects on input usage and clearing

Policies 1 and 2 yield different outcomes because their penalty structures differ. For policy 1, fines increase in H_2. Therefore, the optimal choice of H_2 is a smooth function of other parameters, including c, r, λ, and $P(H_2)$. The higher cost of clearing leads the rancher to intensify. Since expected fines are convex, the policy has the greatest effect on large properties that require large amounts of cleared pasture or inputs to repair degraded pasture as well as properties with a large proportion of remaining forest.[15]

By contrast, policy 2 models a penalty that is invariant in H_2 above 0. This structure results in a discontinuous optimal choice of H_2. Ranchers with small optimal levels of clearing invest in inputs, whereas ranchers with large optimal levels of clearing keep producing at the same level of intensity as they would in the absence of the policy. "Small" areas of clearing are defined by enforcement of the policy β. If β is very large, more ranchers will intensify, whereas when the policy is weak and β is low most ranchers will continue to produce without intensifying. Moreover, the definition of "small" is

[14] If we assume constant returns from inputs, the rancher's decision whether or not to clear is uniform across production areas. If we assume increasing returns from inputs, then we would expect larger ranchers to choose not to clear at proportions H_2^X while small ranchers choose to clear.

[15] In reality, properties vary in their propensity for degradation (a function of slope, weather, and soil characteristics). Following the same logic, properties with higher propensity for degradation would also have larger effects.

relative to the amount of land the rancher has already cleared. Whichever group of ranchers can most efficiently substitute inputs for land chooses not to deforest even at input costs that are sufficiently high, deforestation costs that are sufficiently high, and values of β that are sufficiently low enough to induce inefficient ranches to deforest.

3.4.2 Combining fines with market exclusion

While policies 1 and 2 both slow clearing and increase intensification, they influence distinct types of ranchers. Policy 1 penalizes ranchers according to the area cleared and prevents large clearing events and as a consequence slows clearing on ranches that have the capacity for substantial clearing (e.g. are not land constrained). Policy 2 prevents small amounts of deforestation and thus preserves remaining forest on properties that are relatively land constrained.

We now consider an environment with both policies where the rancher solves:

$$\begin{aligned} Max_{\{H_2,M_2\}} \quad & (1-\mathbb{1}\{H_2>0\}\beta)f((1-\alpha)H_1+H_2,M_2)-rM_2-cH_2-P(H_2) \\ s.t. \quad & H_1+H_2<A. \end{aligned} \tag{14}$$

As under policy 2, the rancher maximizes profits without clearing (i.e. by intensification) and with clearing (i.e. by extensification), and compares the two profit outcomes.

- **Case 1: Intensification ($H_2 = 0$).** This is the same as case 1 of section 3.3, because the rancher does not incur a fine. The rancher compensates for all degradation using inputs, and the input-pasture ratio increases.

- **Case 2: Extensification ($H_2 > 0$).** Notably, the inclusion of fines increases the point of discontinuity that determines whether ranchers deforest, $\tilde{H_2}$. Thus, fewer ranchers choose $H_2 > 0$ than under market exclusion alone. Ranchers that continue to deforest produce at the same input-pasture ratio as they would have if fines alone were implemented, but the loss of $(1-\beta)\%$ of revenue results in a lower choice of H_2 and M_2 than would occur when only fines are involved.

When fines for deforestation are combined with market exclusion the marginal cost of deforestation increases. Enforcement of both policies is the most effective way to incentivize intensification and slow deforestation for properties of all sizes and relative land availability. It increases the number of properties that choose $H_2 = 0$ while continuing to slow deforestation on properties that choose to clear. While all ranchers are more likely to choose $H_2 = 0$ than under policy 2 alone, large ranchers are more affected by the combination of policies because the expected fines are increasing in H_2.

3.5 Testable Hypotheses

Policy 1: A policy of fines-for-deforestation should increase input usage, decrease clearing, and increase productivity. The size of the effect increases relative to the amount of initial pasture, as large property owners need larger areas of newly cleared pasture to replace their degraded pasture, and expected fines are increasing and convex in cleared area. The size of the effect is larger on properties with large proportions of remaining forest.

Policy 2: Deforestation is decreasing in β and productivity is increasing in β, as more ranchers choose $H_2 = 0$ when the penalty for clearing is high. The net effect on input usage is ambiguous, as ranchers increase their use of input if they choose $H_2 = 0$ but decreases their use of input if they choose $H_2 > 0$ due to the decreased marginal revenue of cattle. With decreasing returns to inputs, the policy has a larger effect on properties with small initial areas of pasture. The policy also has a larger effect on properties that have smaller proportions of remaining forest.

4 Data

This section presents our sample, data sources, and descriptions of treatment, outcomes and control variables. It concludes with summary statistics.

4.1 Sample

We analyze a sample of municipalities in Brazil from 2004 - 16. We updated and extended a geocoded map of federally inspected slaughterhouses (SIFs) (Alix-Garcia and Gibbs, 2017) to select municipalities in the supply zones of the G4 slaughterhouses owned by the leaders of the Brazilian cattle industry: JBS, Marfrig, Bertin and Minerva.[16] Our sample is composed of all municipalities in the Amazon biome that have ever had a G4-owned slaughterhouse either in the municipality or within a 100-km buffer. We also test how the policy's effect varies with distance to the nearest slaughterhouse by comparing municipalities with a G4-owned slaughterhouse in their 60, 100, or 140 km buffer − 100 km is the mean distance travelled by a supplier and 40 kilometers is half a standard deviation of the distance from the supplier to slaughterhouses.[17] We include the MPs adjacent to our sample in order to gain power on the identification of the effects of the Priority List without losing the geographical similarities provided by

[16]Within the Amazon, these companies controlled 23 of the 55 federally inspected slaughterhouses in 2016.

[17]These numbers were extracted from the public traceability data of the world largest exporter of meat – JBS – and used over 25,000 mapped properties that supplied the company at any time between 2008 - 15 (see Gibbs et al. 2019).

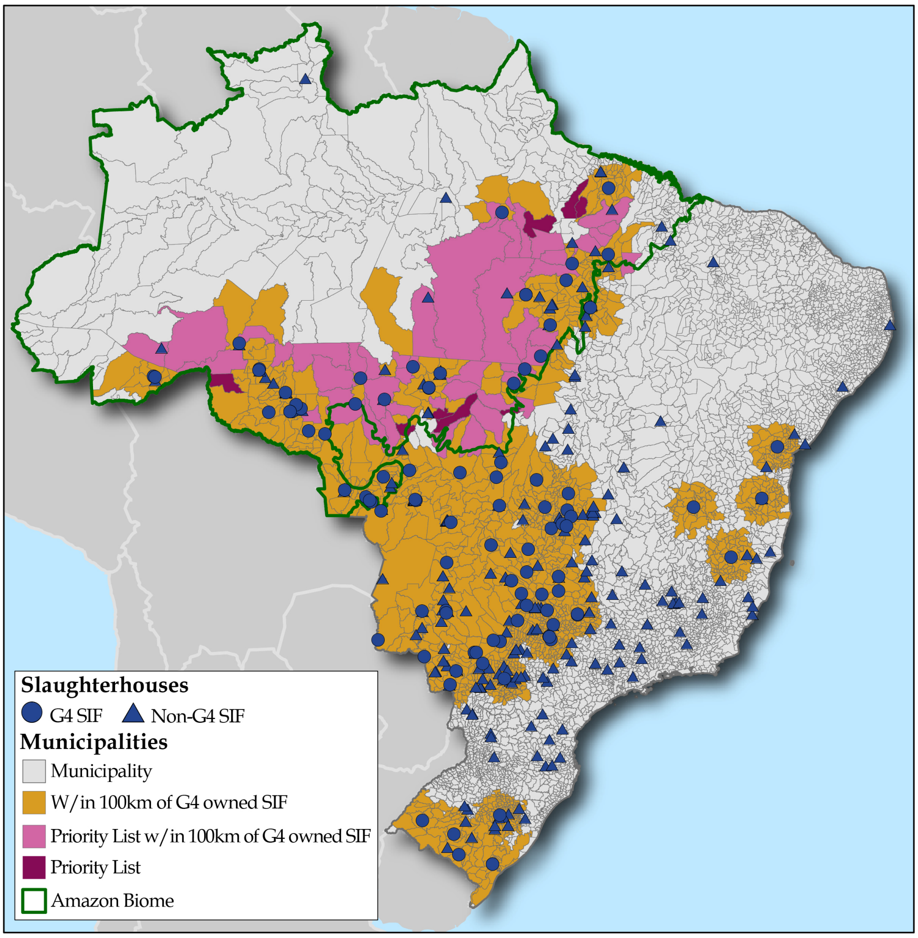


Figure 1: Locations of G4 and non-G4 slaughterhouses and spatial variation of municipalities that have been treated by the G4, the Priority List, or both policies. The main sample is composed of all coloured municipalities within the Amazon biome, and the falsification sample is composed of the colored municipalities outside of the Amazon biome.

our sample definition. This step includes eight more municipalities.[18]

We create a falsification sample of all municipalities outside of the Amazon that are within the 100-km buffer of a G4-owned slaughterhouse. Figure 1 shows the geographical variation of our main sample (restricted to the Amazon biome) as well as the falsification sample (located outside of the Amazon biome). This figure also illustrates the municipalities that were treated by one or both of the policies at any time, as well as the spatial distribution of all the G4-owned slaughterhouses and the non-G4 SIFs of the country. Our main sample has N=242 and the falsification sample has N=1,292 municipalities.

[18]Two MPs remain excluded from the sample: Mucajaí, Roraima (added to the list in 2009 and not yet removed as of 2019) was excluded because it is far north of our sample. Grajaú, Maranhão (added to the list in 2011 and not yet removed as of 2019) was excluded because the majority of its area is located within the Cerrado biome.

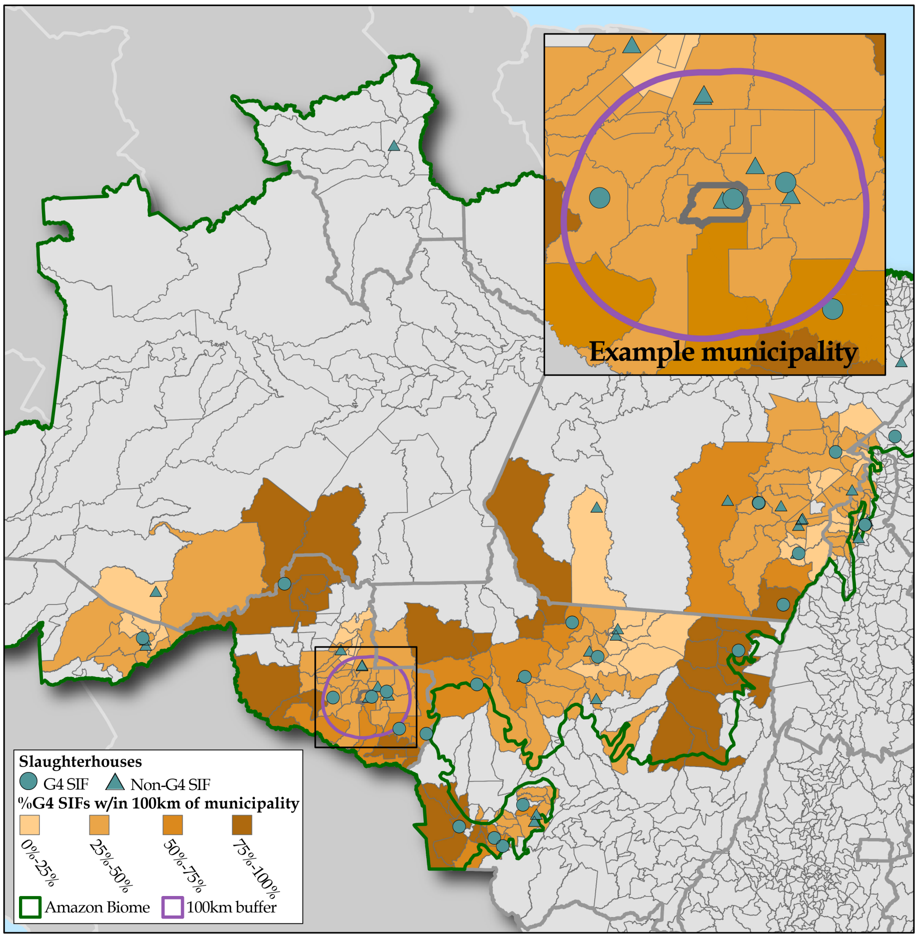


Figure 2: Locations of G4 and non-G4 slaughterhouses in the Brazilian Amazon and spatial variation in average exposure to the G4, which varies due to slaughterhouses openings and closings.

4.2 Data sources and description

Municipalities are exposed to the Priority List from the year they were added to the list until the year they were removed inclusively. Exposure to the G4 Cattle Agreements is calculated for each municipality as the number of slaughterhouses that signed the G4 divided by the total number of SIFs within the municipality buffer (figure 2).[19] This definition of exposure accounts for the influence of nearby G4 plants that are outside the municipal boundaries yet are within the common travel distance of a rancher. The measure varies across both time and space because the G4 did not exist prior to 2009 and SIFs opened and closed throughout the post-G4 period. Table 1 shows how many municipalities were treated by the two policies over time.

[19] Alix-Garcia and Gibbs (2017) used a similar definition of the treatment variable, with the difference that their sample was composed of points within two states of the Amazon.

Table 1: Number of treated municipalities over time

	G4 Cattle Agreements	Priority List	G4 and Priority List
2008	0	36	0
2009	0	42	0
2010	183	42	27
2011	196	47	32
2012	200	48	40
2013	199	44	33
2014	192	39	28
2015	192	39	28
2016	181	39	26

Note. The total number of treated municipalities in a year includes those that were removed from the Priority List during the year.

Our first outcome is productivity, which we define in two ways. First, we estimate the stocking density of cattle (head per hectare of pasture), and next, we divide this density by the sustainable cattle units per hectare to estimate the density as a percentage of its sustainable capacity. Head of cattle per municipality are reported by the Brazilian Institute of Statistics and Geography IBGE (2017), and pasture area is calculated according to MapBiomas (Collection 3).[20] MapBiomas is a yearly land -use dataset that covers all territory of Brazil and is based on Landsat images (30 m resolution). The sustainable cattle units per hectare is based on MODIS satellite imagery and estimated by LAPIG; it corresponds to the production and demand of food for an animal unit (which corresponds to a cow with an approximate weight of 450 kg and requires around 13.5 kg of food per day). Our two measures of productivity provide an unscaled measure of density as well as a measure relative to the land potential, which allow comparison of municipalities across regions and biomes.

Next, we consider investment in inputs using data on rural credit available from the Central Bank of Brazil as a proxy. This credit is paid to producers or cooperatives through the National System of Rural Credit (SNCR). We use two definitions of the credit outcome: first, the municipal rural credit (transformed into 2016 Brazilian reais, using World Bank deflators) divided by the pasture area, and next, the number of contracts for rural credit in the municipality. We include two categories of credit for livestock production: credit for operations and credit for investment.[21] Credit for operations covers the standard cycle of production, including the purchase of fertilizer, animal feed or nutritional supplements, and animals for fattening (only when purchased by an independent rural producer). Credit for investment covers

[20] We consider pasture to be the sum of pasture areas and the pasture or agriculture areas provided by MapBiomas. The pasture or agriculture category is known to be primarily comprised of pasture area but can contain patches of agriculture.

[21] Disaggregated results for those two categories are presented in Appendix C.

the construction or renovation of permanent installations (such as rotational grazing or a confinement), purchase of equipment that will last for more than five years (e.g., tractors and machinery), irrigation or drainage work, pasture investment (e.g., recuperation, soil protection, or correction), or animals for reproduction.[22] All of these investment projects require high up-front costs, and many increase long-run productivity. We exclude credit for commercialization because it is not related to potential increases in productivity.

According to the Brazilian Central Bank, SNCR was founded in 1965 by law 4.829 with the objective of increasing agricultural productivity. Today, producers are eligible to receive the subsidized credit through public and private financial institutions. In 2017, more than half of agricultural properties that received credit were the recipients of a line of government-subsidized credit. These included the National Program of Strengthening Family Agriculture and the National Program of Support for Medium-sized Producers, two hallmark examples of the Brazilian government's efforts to offer credit to small and medium-sized rural producers (IBGE, 2019). Although they are subsidized, not all lines of credit offered under SNCR are limited to small and medium-sized producers (Banco do Brasil, 2019). The use of credit as a proxy for investment follows de Castro and Teixeira (2012), who use rural credit as proxy for input expenditure and find it to be highly correlated with demand for inputs and total agricultural output. Although credit is an imperfect measure of investment in inputs, it offers the clear advantage of creating a panel otherwise not available for agricultural investment in Brazil (Agricultural Census data are only available once every decade).

We also provide complementary clearing results in appendix F for comparison with the existing literature on avoided deforestation from the two policies. We consider clearing of natural vegetation when the land is subsequently used for pasture (extracted from MapBiomas). Two measures are used: first, clearing in hectares and second, clearing as a percent of the total hectares in the municipality. Reforestation is not considered in this analysis because it is not incentivized by the policies we study.

Additional variables come from other sources. For heterogeneous analyses, we use data from the 2006 Agricultural Census to estimate the percentage of properties in a municipality that are over 500 hectares. We use the baseline natural vegetation area (MapBiomas) to estimate the percentage of the municipal area in natural vegetation (used for heterogeneous analysis and as control). Finally, we

[22] Although both the operation and the investment credit fund the purchase of animals, credit for investment only funds the purchase of animals for reproduction, which is unlikely to cause an immediate increase in the region's productivity. Rather, it could lead to a larger increase in productivity in subsequent years. Unfortunately, we are unable to distinguish between credit used for the acquisition of animals and that used for the purchase of inputs or machinery. However, we test the policy's effect on total herd size in appendix G to provide additional understanding of changes that occurred during our study-period.

create a single category that combine various protected areas: indigenous territory (from the National Indian Foundation), and strict protection and sustainable use areas (from the Brazilian Ministry of the Environment).

Summary statistics are presented in appendix B for our treatments, outcomes, and the additional covariates presented in this section. In the table, we show the mean and standard deviations for both the Amazon sample and the falsification sample.

5 Estimation Strategy

We identify the effect of the G4 and the Priority List using variation in the exposure of a municipality to each policy over time. We estimate panel regressions with municipality and time fixed effects using the following specification:

$$Y_{mt} = \gamma_m + \theta_t + \beta_1 G4_{mt} + \beta_2 MP_{mt} + \beta_3 G4_{mt} * MP_{mt} + \delta' \mathbf{X}_{mt} + \epsilon_{rt}, \tag{15}$$

where Y_{mt} is cattle productivity, rural credit or clearing of natural vegetation, $G4_{mt}$ is a continuous measure of the level of exposure to the G4 and MP_{mt} represents the binary exposure to the Priority List. The matrix $\mathbf{X}_{mt}$ is composed of the total number of SIFs in the municipality or its buffer to control for openings and closings of slaughterhouses over time as well as protected areas per municipal ha which change over time and restrict the available land. Municipality fixed effects (γ_m) control for unobservable fixed characteristics of the municipality, including land quality, and time fixed effects (θ_t) control for potential shocks affecting all municipalities during the same year. We cluster our robust standard errors (ϵ_{mt}) at the microregion level.[23]

When G4 companies choose to open a slaughterhouse, they are likely to prefer municipalities with a higher productivity or skill level. To include municipalities that never had a G4-owned slaughterhouses nearby could bias our estimate upward, thus we restrict our sample to those municipalities that have ever had a G4-owned slaughterhouse or the adjacent MPs.[24] We prefer this strategy to a matching regression because slaughterhouse site selection reveals preferences associated with both observable characteristics of the location (e.g. productivity) and unobservable ones (e.g., skill level) and a matching regression could consider only observable characteristics. In addition, our sample of municipalities is connected to the global beef market due to being close to a G4-owned slaughterhouse. Because these slaughterhouses

[23]There are 66 microregions in Brazil, 22 of which are in the Amazon biome.
[24]A robustness test without the MPs adjacent to our sample is presented in appendix E.

are exporters, their prices are based on global prices rather than solely on local supply. Thus, potential concerns over general equilibrium effects from the policies are less salient.

Most of the MPs naturally fall within the reach of G4 companies (as shown in figure 1). With the exception of three MPs, all municipalities that have ever been on the Priority List have also been within 140 km of a G4-owned slaughterhouse. This indicates that MPs shared observable and unobservable characteristics with municipalities where G4 companies chose to open slaughterhouses. Because of the preferences revealed by slaughterhouse site locations, it is possible that productivity and investment increase more in the municipalities that are closest to the G4. If this is the case, our choice of G4 municipalities as a counterfactual for MPs offers a lower bound estimate of the effect of the Priority List.

6 Results

In this section, we present results of the impact of the G4 and the Priority List on productivity and investment in inputs, followed by heterogeneous results and tests of parallel pre-trends.

6.1 Effects of the G4 and the MPs on productivity and investment in inputs

We find that exposure to both the G4 and the Priority List had a positive effect on productivity (table 2). In our preferred specification with the full set of controls, the average municipality that was exposed only to the G4 (hereafter G4-only) increased productivity by 0.08 head/ha of pasture compared to a municipality with no exposure.[25] These municipalities were 2.52 percentage points closer to producing at their sustainable capacity. In MPs that were never exposed to the G4 (hereafter MP-only), being added to the Priority List increased productivity by 0.10 head/ha of pasture. These municipalities were 2.50 percentage points closer to producing at their sustainable capacity, although these results are not precisely estimated. When municipalities were exposed to both the G4 and the Priority List (hereafter G4-MP), they saw an increase of 0.17 head/ha of pasture on average, and they were 4.77 percentage point closer to producing at their sustainable capacity.[26]

Exposure to the G4 increased the use of credit by R$33.95/ha of pasture in G4-only municipalities. These municipalities also had 60.04 more contracts on average than municipalities with no exposure. This corresponds to an additional 5.35 billion reais in the use of credit and 81,556 credit contracts.[27] We

[25] The mean level of G4 exposure in years that municipalities were exposed to the G4 and not the Priority List was 0.55. All results corresponding to G4-only are calculated according to the mean level of exposure.

[26] The mean level of G4 exposure in years that municipalities were exposed to the G4 and the Priority List was 0.66. All results corresponding to G4-MP are calculated according to the mean level of exposure.

[27] We estimate individual year effects for each municipality using exposure to the policy and sum these to estimate the

find no evidence of an effect of the Priority List on credit. These results incorporate both the demand for credit by ranchers and the availability of credit from banks. As such, the estimated increase in credit following the G4 could have been caused by an increase in demand or an increase in supply by banks in response to the policy (if unmet demand existed prior to the policy). We provide additional insights in this regard in the falsification test presented in section 7.1. Similarly, the Priority List intended that banks apply environmental laws regarding credit more thoroughly in MPs. This means that properties with illegal deforestation could have suffered additional restrictions that counteract any increase in demand by intensifying properties and thereby result in a null aggregate effect on credit.

In appendix C, we test types of credit separately and see that the G4 had a larger effect on credit for investment, which includes purchase of tractors, infrastructure for production, animals for reproduction, and irrigation. Indeed, there were 47.13 more contracts for investment for G4-only municipalities compared to 12.92 more contracts for operations. This suggests that many ranchers took on large-scale projects in response to the G4. Some increased their use of inputs such as fertilizer or feed or their purchase of animals for fattening, which are covered by operations, but this was a small effect compared to investment in projects for long-run productivity.

6.2 Heterogeneous effects

6.2.1 Effects by property size

The theoretical micromodel suggests that the Priority List has heterogeneous impact relative to property size (section 3.5). To test this hypothesis, we interact the baseline percentage of properties in a municipality that are more than 500 hectares with the exposure to the G4 and the Priority List. Results are reported in table 3.

The interaction between the percentage of large properties and exposure to the Priority List is positive and significant for our measures of productivity. The average MP had 12.76% of properties larger than 500 hectares with a standard deviation of 0.13. We find a net increase of 0.10 head/ha of pasture in the average MP after addition to the Priority List, which matches our result from table 2. Here we see that a one standard deviation increase in the proportion of large properties expanded the effect by an additional 0.13 head/ha of pasture, doubling the effect for the average municipality. Moreover, the average MP was 2.40 percentage points closer to its sustainable capacity after addition to the list, but a one standard

total effect of the policy in our time frame. To estimate the value in Reais using the policy's effect on credit per hectare, we multiplied by the pasture area in the municipality, which had an average of 167,397 hectares in our treated sample between 2008 and 2016.

Table 2: Estimated effect of the G4 and the Priority List on cattle productivity and credit

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4	0.155**	0.154**	4.622**	4.588**	60.095**	61.738**	103.221***	109.196***
	(0.056)	(0.056)	(1.723)	(1.711)	(23.537)	(23.449)	(36.194)	(36.728)
MP	0.117*	0.103	2.870	2.496	21.734	23.947	15.530	7.101
	(0.062)	(0.063)	(1.819)	(1.839)	(20.049)	(19.951)	(54.894)	(56.193)
G4 × MP	-0.054	-0.051	-1.238	-1.149	-70.277**	-72.432***	-271.642	-277.252*
	(0.061)	(0.062)	(2.141)	(2.138)	(25.706)	(25.394)	(158.296)	(159.945)
Lincom								
G4 + MP	0.218**	0.207**	6.253**	5.935**	11.552	13.253	-152.891	-160.955
	(0.088)	(0.084)	(2.681)	(2.602)	(20.764)	(19.730)	(128.683)	(131.366)
Observations	3,144	3,144	3,144	3,144	3,097	3,097	3,097	3,097
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Time & municipality FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

deviation increase in large properties corresponded to an additional percentage point increase of 3.82.[28] As in the main results, the policy had a modest effect on average, but this analysis demonstrates that the results in table 2 mask increases in productivity in municipalities with large ranches.

Credit per hectare of pasture also increased with the proportion of large ranches in MPs. The average MP saw an increase in credit of R$22.63/ha of pasture, but a one standard deviation increase in large properties resulted in an additional increase of R$52.43/ha of pasture. While the interaction term in the model that estimated the effect on the number of contracts is also positive, it is not statistically significant. These results show that large ranches increased credit, suggesting they were the same ones that intensified, leading to an increase in the total value of credit/ha of pasture, but not increasing the number of contracts.

6.2.2 Effects of land constraint

The Priority List, according to our theoretical model, should have a stronger effect on properties that are not land-constrained (i.e., properties that have large amounts of remaining forest), while the G4 should incentivize intensification on properties that are land constrained (i.e., properties that have little remaining forest). We test this using municipal-level forest and natural vegetation in 2006 as a percent of total municipal area. While this proxy does not measure the land constraint for each property owner, it represents the general availability of land for pasture expansion within the municipality. Results are presented in table 4.

The interaction between the percentage of forest and exposure to the G4 is negative and significant for the productivity measures and the value of credit/ha of pasture. This indicates that the G4 had the smallest impacts on productivity and credit in municipalities with a high percentage of forest cover and conversely, the largest impacts in municipalities with a low percentage of forest cover. Numerically, this corresponds to an increased productivity of 0.10 head/ha of pasture in the average G4-only municipality (or a 3.11 percentage point increase relative to sustainable carrying capacity), while for those municipalities with less forest cover, estimated as a one standard deviation decrease in baseline forest, this leads to a further 0.07 increase in head/ha of pasture (or a 2.40 percentage point increase relative to sustainable capacity).[29] Similarly, the average G4-only municipality saw an average increase in credit of $R37.56/ha of pasture, while for those municipalities with less forest cover, the increase was a further $R17.89/ha of pasture. We also note that there is no heterogeneous impact for the number of

[28]This interpretation is for both MP-only and G4-MP since the linear combination of all terms, including interaction terms, is statistically insignificant.

[29]The average G4-only municipality had 48% of remaining forest, with a standard deviation of 0.27.

Table 3: Heterogeneous effects of the Priority List on productivity and credit by property size

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4	0.147**	0.149**	4.307**	4.305**	60.072*	62.279**	111.003**	122.045**
	(0.056)	(0.057)	(1.688)	(1.672)	(28.900)	(28.990)	(40.662)	(43.642)
MP	-0.021	-0.038	-1.147	-1.607	-34.846	-32.196	3.251	-5.771
	(0.107)	(0.104)	(3.186)	(3.122)	(25.550)	(25.111)	(93.339)	(94.966)
G4 × MP	0.017	0.020	0.888	0.978	-27.993	-29.558	-321.270	-324.798
	(0.100)	(0.101)	(3.551)	(3.559)	(36.618)	(35.938)	(218.694)	(220.045)
Large properties × G4	0.052	0.026	2.688	2.143	-14.867	-21.490	-92.223	-152.427
	(0.236)	(0.243)	(7.030)	(7.184)	(149.678)	(146.798)	(238.468)	(245.674)
Large properties × MP	1.063*	1.084*	30.814*	31.410*	434.769*	429.699*	89.972	93.607
	(0.555)	(0.551)	(16.225)	(16.153)	(234.863)	(232.137)	(314.541)	(315.098)
Large properties × G4 × MP	-0.534	-0.523	-16.496	-16.170	-322.941	-326.144	459.877	460.180
	(0.508)	(0.526)	(16.076)	(16.582)	(274.607)	(270.692)	(652.559)	(645.665)
Lincom								
G4 + Large properties x G4	0.200	0.175	6.995	6.448	45.204	40.789	18.780	-30.382
	(0.232)	(0.238)	(7.000)	(7.147)	(134.606)	(131.441)	(223.723)	(226.014)
MP + Large properties x MP	1.042**	1.046**	29.667**	29.803**	399.923*	397.503*	93.224	87.835
	(0.460)	(0.460)	(13.390)	(13.407)	(212.209)	(209.881)	(225.275)	(224.149)
G4 + MP + G4xMP + Lg propxG4 + Lg propxMP + Lg propxG4xMP	0.707	0.717	20.165	21.060	122.186	82.588	571.881	192.835
	(0.516)	(0.465)	(17.990)	(16.039)	(110.460)	(97.230)	(648.493)	(496.096)
Observations	3,144	3,144	3,144	3,144	3,097	3,097	3,097	3,097
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

contracts. This is consistent with our theory since municipalities with a high percentage of forest cover could also have a proportionally smaller number of owners. Our estimation supports the hypothesis that property owners in municipalities with high areas of remaining forest stand to gain by continuing to clear large areas, while those in municipalities with less remaining forest are more likely to comply with the zero-deforestation policy.

While we do not find a significant interaction between the Priority List and forest cover, we find that the Priority List offset the low productivity response to the G4 in highly forested municipalities. This demonstrates the interaction of the two policies; the Priority List complements the G4 by leading more ranchers to choose not to deforest or to clear smaller areas. Despite having more remaining forest than G4-only municipalities, the average G4-MP increased productivity by 0.13 head/ha of pasture, or an increase of 3.49 percentage points relative to sustainable capacity.[30]

6.2.3 Effects of distance to a G4-slaughterhouse

The theoretical model predicts that the G4 policy's effect is increasing in β (the penalty on income that ranchers incur after deforestation). While the measure of the exposure to the G4 captures this variation in β, another factor that affects the severity of the penalty is the distance from the slaughterhouse. This penalty should be highest in municipalities that are nearest to G4 slaughterhouses, as ranchers with deforestation would need to increase their transportation costs to sell to a non-G4 slaughterhouse. Here, we consider the heterogeneous effects of the G4 exposure according to the suppliers' distance to the slaughterhouse using a sample that includes all municipalities in a 140-km buffer of a G4-owned slaughterhouse. We include three mutually exclusive indicators: first, municipalities within the 60 km buffer (G4 $<$ 60 km); next, municipalities exposed to the G4 between the 100 and 60 km buffer (G4 60-100 km); and finally, municipalities exposed to the G4 only in the 140 km buffer (G4 100-140 km). We interact these indicators with the Priority List treatment. Results are presented in table 5.

The G4 had the largest effect on productivity and credit close to the slaughterhouse. The coefficients for head/ha of pasture are 0.42 when the buffer is under 60 km, 0.32 for the 60-100 km buffer, and 0.11 for the 100-140 km buffer (statistically insignificant). The coefficients for the value of credit per hectare of pasture are 293.87 in the less than 60 km buffer, 290.68 for the 60-100 km buffer, and -43.74 for the 100-140 km buffer (also statistically insignificant). MPs increased head/ha of pasture by 0.20 and their density relative to capacity increased by 5.62 percentage points in this specification.

We find that combining the policies resulted in the largest effect in the 60 - 100 km buffer. For a

[30]The average G4-MP had an average of 70% remaining forest with a standard deviation of 0.17.

Table 4: Heterogeneous effects of the Priority List on productivity and credit by percent forest cover

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4	0.405**	0.423**	13.013**	13.531**	128.466**	127.070**	21.394	24.604
	(0.150)	(0.157)	(4.646)	(4.882)	(45.964)	(46.005)	(89.189)	(92.075)
MP	0.368	0.460	12.571	15.361	147.819	140.549	-160.145	-143.428
	(0.336)	(0.353)	(9.764)	(10.393)	(103.740)	(105.171)	(249.482)	(251.135)
G4 × MP	-0.332*	-0.360*	-9.995**	-10.827**	-187.212*	-185.015*	24.753	19.701
	(0.170)	(0.174)	(4.531)	(4.633)	(96.649)	(97.098)	(586.804)	(586.145)
Percent forest × G4	-0.462**	-0.496**	-15.443**	-16.470**	-125.583**	-122.831**	151.160	144.831
	(0.178)	(0.190)	(5.538)	(5.936)	(51.718)	(51.658)	(133.228)	(138.768)
Percent forest × MP	-0.343	-0.498	-13.305	-17.979	-174.194	-162.023	244.029	216.041
	(0.474)	(0.496)	(13.933)	(14.835)	(124.084)	(126.722)	(298.879)	(303.189)
Percent forest × G4 × MP	0.510**	0.558**	16.125**	17.579**	195.489	191.645	-464.103	-455.263
	(0.240)	(0.248)	(6.920)	(7.082)	(114.515)	(115.358)	(882.325)	(879.531)
Lincom								
G4 + Percent forest x G4	-0.056	-0.073	-2.430	-2.939*	2.883	4.239	172.554**	169.435**
	(0.047)	(0.049)	(1.466)	(1.511)	(22.218)	(22.046)	(62.706)	(64.488)
MP + Percent forest x MP	0.025	-0.038	-0.734	-2.617	-26.376	-21.474	83.884	72.612
	(0.156)	(0.161)	(4.626)	(4.902)	(24.948)	(25.965)	(66.479)	(70.160)
G4 + MP + G4xMP + Pct forxG4 + Pct forxMP + Pct forxG4xMP	0.478	0.087	12.961	1.196	171.997*	-10.604	-207.665	-193.515
	(0.282)	(0.209)	(8.695)	(6.850)	(96.930)	(27.154)	(854.987)	(340.660)
Observations	3,144	3,144	3,144	3,144	3,097	3,097	3,097	3,097
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

municipality within the smallest buffer (less than 60 km), the interaction term suggests that addition to the Priority List had no effect on productivity if it had already been exposed to the G4. This corresponds with the theoretical model, as the stronger influence of the G4 leads more properties to choose not to deforest and be therefore unaffected by the Priority List. In the 60 - 100 km buffer, however, there is one set of ranchers who continue to deforest despite the G4. These ranchers are influenced by the Priority List, which leads to a strong effect in this buffer. Further, we find additional evidence that G4 municipalities on the Priority List had a smaller increase in credit than non-MPs.

6.3 Parallel trends test

The validity of our estimates depends on the assumption that in the absence of the G4 and the MPs, and while controlling for municipality and time fixed effects as well as our set of controls, municipalities would have followed parallel trends. This assumption, which cannot be tested directly, may be verified by comparing the pre-trends for the municipalities before the programs with a model from the event study literature:

$$Y_{it} = \tilde{\alpha_i} + \tilde{\beta_t} + \sum_{k=-3}^{4} \tilde{\lambda_k} \mathbb{1}\{\hat{G}_{mt} = k\} + \sum_{k=-3}^{4} \tilde{\gamma_k} \mathbb{1}\{\hat{M}_{mt} = k\} + \tilde{\epsilon_{rt}}. \tag{16}$$

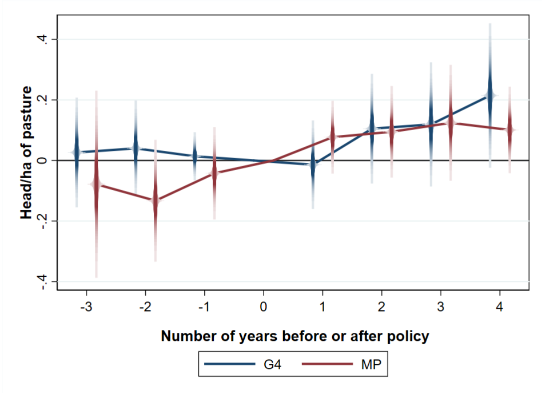
Here $\hat{G}_{mt}$ is the difference between year t and the first year of G4 exposure, while $\hat{M}_{mt}$ is the difference between year t and the first year the municipality is placed on the priority list. To obtain a balanced panel, we focus on municipalities that had data both three years before the policy and four years after. We drop observations that are outside of this window. For our estimates of β to be unbiased in equation 15, λ_{-3} through λ_{-1} and γ_{-3} through γ_{-1} should not be different from zero. We graph the point estimates and 95 percent confidence intervals of λ_{-3} through λ_4 and γ_{-3} through γ_4 in figure 3.

The coefficients of the pre-trends suggest that our sample choice circumvents the problem of companies selecting municipalities based on productivity and investment. Neither policy had a statistically significant lead-up effect on productivity or investment in the year immediately before treatment, and the overall trends support the statistical validity of our estimation strategy. Thus, we conclude that although MPs were chosen based on deforestation, the municipalities that were ultimately placed on the Priority List were not on a significantly different productivity or investment trajectory than municipalities that had ever been within reach of a G4, but never selected to be on the Priority List.

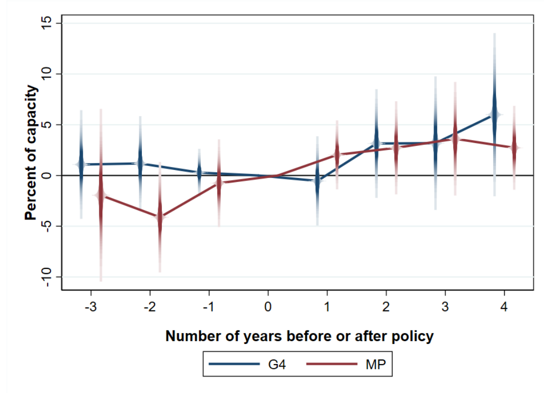
Table 5: Effects of the G4 and the Priority List on cattle productivity and credit according to the municipality's distance to a G4-slaughterhouse

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4 < 60 km	0.419***	0.423***	13.359***	13.460***	293.979**	293.872**	151.547***	158.729***
	(0.088)	(0.094)	(2.859)	(3.043)	(131.288)	(133.052)	(36.864)	(36.921)
G4 60-100 km	0.305***	0.316***	9.502**	9.830**	290.326**	290.676*	174.248***	177.730***
	(0.104)	(0.109)	(3.478)	(3.620)	(137.785)	(140.331)	(53.699)	(53.490)
G4 100-140 km	0.115	0.114	3.174	3.241	-43.357	-42.744	190.515***	175.773**
	(0.130)	(0.126)	(4.359)	(4.233)	(118.771)	(120.080)	(63.577)	(66.294)
MP	0.214**	0.199**	6.050**	5.619**	140.482	140.074	11.202	5.833
	(0.076)	(0.076)	(2.264)	(2.267)	(98.043)	(94.920)	(56.189)	(55.758)
G4 < 60 km × MP	-0.278**	-0.278**	-8.726**	-8.688**	-227.496*	-227.223*	-355.472	-361.768
	(0.125)	(0.127)	(4.106)	(4.155)	(110.320)	(110.839)	(256.016)	(257.569)
G4 60-100 km × MP	0.038	0.050	2.270	2.678	-195.828*	-195.088*	-150.247*	-155.509*
	(0.130)	(0.133)	(4.290)	(4.385)	(111.500)	(110.172)	(79.736)	(79.718)
G4 < 100-140 km × MP	-0.050	-0.029	-0.769	-0.162	104.407	104.826	-47.770	-35.645
	(0.124)	(0.126)	(3.744)	(3.718)	(128.056)	(132.690)	(83.102)	(82.965)
Lincom								
G4 < 60 km + MP	0.355***	0.344***	10.682**	10.391**	206.965	206.722	-192.723	-197.206
	(0.121)	(0.121)	(4.015)	(4.050)	(125.754)	(123.656)	(224.474)	(226.437)
G4 60-100 km + MP	0.557***	0.566***	17.822***	18.126***	234.981*	235.661*	35.203	28.054
	(0.103)	(0.105)	(3.535)	(3.584)	(125.121)	(126.042)	(58.390)	(56.681)
G4 100-140 km + MP	0.278	0.285	8.455*	8.698*	201.532*	202.155*	153.947	145.961
	(0.173)	(0.174)	(4.544)	(4.581)	(108.963)	(109.797)	(111.579)	(113.370)
Observations	3,625	3,625	3,625	3,625	3,573	3,573	3,573	3,573
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

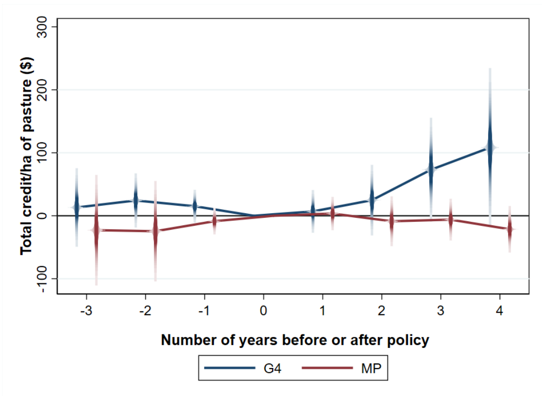
Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.



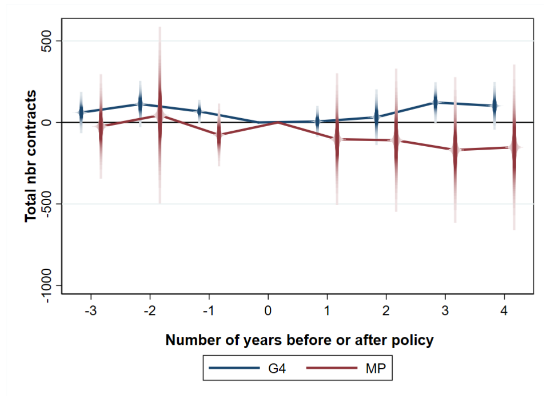
(a)



(b)



(c)



(d)

Figure 3: Leading and lagging effects of the G4 and Priority List. Estimates obtained using the specification with a balanced panel of municipalities covering the seven years surrounding the introduction of the two policies of interest.

7 Robustness checks

Here, we discuss identification challenges and support our results with falsification tests and robustness tests. We also provide complementary results on clearing and on underlying components of productivity.

7.1 Falsification test

We examine whether our results were driven simply by the presence of the G4 slaughterhouse, rather than by the G4 Cattle Agreements. After the initial enforcement of the G4 Cattle Agreements, all variation in treatment came only from openings and closings of slaughterhouses. Our results could therefore be driven by the opening of a slaughterhouse that stimulates changes in productivity, rather than by the G4 Cattle Agreements policy. Our falsification test uses municipalities outside of the Amazon biome and integrates biome specific time trends to control for differences across the four biomes outside of the Amazon.[31] Municipalities with a G4 slaughterhouse outside of the Amazon have faced all the same pressures caused by having a G4 slaughterhouse except the zero-deforestation policy, which was enforced only in the Amazon biome.

Our results support the premise that the increase in productivity and credit was due to the G4 Cattle Agreements, rather than merely the result of proximity to the G4-owned slaughterhouses. We find that exposure to the G4 had no effect on cattle productivity or the value of credit outside of the Amazon biome (table 6). In our preferred specification with biome time trends, there was an increase in contracts, although this result is only significant at the 10 percent level. Differences in biome time trends seem to explain a large proportion of the differences in the change in number of contracts. Indeed, biomes are subject to distinct agricultural development, distribution of landownership, and policy pressures that may affect their land investment dynamics (see e.g., Rausch et al. 2019; Soares-filho et al. 2014). As shown in the table that excludes this control (appendix D), all results on productivity and value of credit per hectare are consistent with table 6. However, the coefficient associated with the number of contracts has a larger point estimate and is statistically more significant when we do not include biome time trends. Overall, since the estimated coefficients associated with the value of credit/ha of pasture are negative, the result tends to indicate that average value per contract decreased for those municipalities with higher G4 treatment outside the Amazon. This also suggests that our conclusions from the falsification test are not undermined.

[31] This control is implicitly used in all our regressions, but since there is only one biome in our main sample, it simply corresponds to the time fixed effects.

Table 6: Falsification test – Estimated effect of the G4 outside the Amazon on cattle productivity and credit

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4 - out of the Amazon	-0.236	-0.362	-3.553	-5.896	-204.644	-110.643	91.039***	38.984*
	(0.165)	(0.257)	(2.787)	(4.088)	(229.314)	(198.775)	(31.367)	(20.862)
Observations	16,751	16,751	16,751	16,751	16,537	16,537	16,537	16,537
Pre-period mean (G4)	1.8	1.8	43.7	43.7	335.9	335.9	172.3	172.3
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Biome x Time		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. * p< 0.10, ** p<0.05, *** p<0.01.

7.2 Sample limited to 2004 - 12

If ranchers with high productivity and high levels of investment favor areas around G4 slaughterhouses but avoid MPs, then ranchers might have left MPs and moved to G4 municipalities. This would bias our estimate of the G4 impact upward and the estimate of the Priority List downward. Similarly, if G4 plants were likely to cease their slaughtering activities where the policy environment was the most restrictive, our results could be biased. To address these concerns, we limit our sample to 2004 - 12. This implicitly allows producers three years to adopt techniques that improve productivity, while limiting relocation of ranchers and slaughterhouses, as the process of opening, closing, or relocating a ranch or slaughterhouse is lengthy and bureaucratically complex. Results are presented in table 7.

This robustness test supports the conclusion that our results are not driven by endogenous sorting of cattle ranchers and openings of G4 slaughterhouses after the announcement of the policies. Indeed, we find a nearly identical response in productivity to the G4 in the short sample (although the effect on the value of credit per hectare is no longer statistically significant).

Conversely, we find a stronger productivity response to the Priority List in this time period. In the first four years of the policy, MP-only saw an increase of 0.14 head/ha of pasture compared to 0.10 over the full period, while G4-MP saw an increase of 0.20 head/ha of pasture compared to 0.16 over the full period. This is plausible, given anecdotal reports that the policy was pursued more aggressively during its early stages.

Table 7: Sample limited to 2004-12 – Estimated effect of the G4 and the Priority List on cattle productivity and credit

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4	0.167*	0.174*	5.254*	5.394*	27.891	30.029	106.214**	89.633**
	(0.094)	(0.098)	(2.923)	(3.013)	(21.878)	(23.323)	(40.626)	(42.613)
MP	0.163***	0.144***	4.357***	3.824***	9.891	10.902	-8.920	-17.136
	(0.048)	(0.045)	(1.394)	(1.327)	(13.388)	(13.332)	(63.711)	(65.252)
G4 × MP	-0.079	-0.084	-2.580	-2.696	-47.324**	-49.358**	-314.339*	-298.549*
	(0.084)	(0.086)	(2.953)	(2.908)	(18.650)	(18.577)	(164.674)	(156.412)
Lincom								
G4 + MP	0.251**	0.233*	7.030*	6.522*	-9.542	-8.427	-217.045	-226.053
	(0.118)	(0.113)	(3.387)	(3.255)	(22.111)	(21.151)	(150.845)	(154.352)
Observations	2,176	2,176	2,176	2,176	2,172	2,172	2,172	2,172
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

7.3 Restriction to municipalities that had a G4 slaughterhouse at any time

In order to restrict our analysis to the most comparable sample, we exclude MPs that never had a G4 slaughterhouse within their buffer (appendix E). Again, we find that the policies increased productivity, although we lose significance when estimating the main effect of the Priority List due to loss of observations in the priority municipalities sample.

7.4 Effect of the G4 and Priority List on clearing, pasture area, and head of cattle

Finally, we test the policy's effect on the underlying components of productivity: deforestation, total pasture area, and total head of cattle. As previously shown by Alix-Garcia and Gibbs (2017), we find no evidence that the G4 reduced clearing (appendix F), despite having a significant effect on productivity. This could be because ranchers experienced relatively small amounts of degradation during the time period. They may have invested in productivity with the awareness that degradation would continue, but in the absence of the policy they would have undertaken relatively small amounts of clearing in the short time frame. We show there was a larger increase in credit for investment, which covers "lumpy" goods like tractors and infrastructure. This strengthens the likelihood that ranchers invested in productivity while considering future production seasons.

We find supportive evidence that the MPs reduced clearing. This is consistent with literature which consider the policy's effect up to 2012 (at the most recent) and find that the policy significantly reduced clearing (Assunção and Rocha, 2014; Cisneros et al., 2015; Arima et al., 2014; Assunção et al., 2019). When we limit our sample to 2004-12, we find that MP-only had 5,146 fewer hectares of deforestation per year after the policy, while G4-MP had 6,050 fewer hectares of deforestation on average. When we consider the policy's effect through 2016, we find a smaller but still statistically and economically significant effect of 3,385 fewer hectares of deforestation per year in MP-only and 3,781 fewer hectares in G4-MP.

The ratio of the number of head of cattle to the total municipal area increased after both policies. The average G4-only municipality saw an increase of 0.023 head/ha, while an MP-only saw an increase of 0.030 head/ha, and a G4-MP saw an increase of 0.046 head/ha. However, total pasture area as a proportion of total municipal area did not change differently in response to either policy (appendix G). Over the lifetime of the policies, the increase in productivity was accompanied by an increase in the number of animals without an expansion of pasture area caused by the policies.

Although the policies could have increased productivity through the purchase of animals, a short run direct effect is ruled out by our implicit assumption that ranchers do not stock cattle at less than the optimal capacity given prices. We have no evidence that either policy directly affected the price of inputs. Moreover, since the price of cattle is connected to the global market, local prices effects should not have led ranchers to purchase additional animals above the level they selected prior to the policy. Instead, we note that while our theoretical model is limited to two periods, our econometric analysis considers six years following the beginning of the G4 and eight years after the release of the first Priority List. It is plausible that initial increases in productivity motivated medium or long-run increases in herd size.

The theoretical model predicts that ranchers will reduce clearing in response to both policies, and this reduction is part of what increases the capital-to-land-ratio. In reality, ranchers may have also increased productivity per hectare of pasture by abandoning pasture. We do not consider reforestation or abandonment in our measure of deforestation, but these would be captured by the total pasture area.

8 Conclusion

This article investigates how environmental policies modify the allocation of resources for agricultural production. We show evidence that anti-deforestation policies affected input usage in the Brazilian Amazon, a region of historically low-density cattle production. Between 2008-16, both the G4 and the Priority List increased productivity (6.10% and 11.54% respectively), with the greatest increase occurring when municipalities were subject to both policies (16.36%). The G4 also increased credit uptake (most of which was for investment goods like tractors or rotational grazing), while we do not find an effect from the Priority List. Productivity and investment increased more in municipalities closer to G4 slaughterhouses (because ranchers faced the highest costs if they were excluded from the supply chain following deforestation) and with less remaining forest (because ranchers had less to gain by violating the zero-deforestation requirement), while the largest effects from the Priority List were found in municipalities with a high proportion of large ranches (as these ranches faced a greater risk of being fined should they deforest).

Our analysis brings new evidence of the impacts of environmental regulation on productivity. We are the first to examine empirically the effect of the Priority List on investment and the effect of a market exclusion policy on both productivity and investment. We expand the micromodel of Koch et al. (2019) by integrating a crucial mechanism, namely pasture degradation, and we create the first theoretical study of a market exclusion policy. We further document, both theoretically and empirically, how the fines-for-deforestation and the market exclusion policies interact and how they can be complementary because they affect producers in different ways according to their characteristics.

We note two caveats. First, with our municipal-level data, we are unable to precisely isolate the reason why productivity and investment increased while deforestation patterns did not change following the G4. One possible reason is that the G4 increased high-capacity confinement operations that serve as intermediaries in order to avoid direct monitoring of ranchers with deforestation by the slaughterhouses. To better understand the extent to which this could explain our results, further work should quantify the change in market power for confinements and the likelihood of new confinements near G4 slaughterhouses. Second, we cannot disentangle the changes in credit availability from any change in demand for credit. On one hand, banks could have increased the supply of credit near G4 slaughterhouses. On the other hand, credit availability could have been reduced in MPs following the policy. While this can threaten our identification, especially in the case of the G4, we argue that the falsification test results (based on a sample of municipalities with G4-owned slaughterhouses outside of the Amazon) provides credible arguments that credit supply does not necessarily increase near G4-owned slaughterhouses.

In spite of these limitations, our paper has broader implications for environmental and agricultural policies. First, we confirm that environmental policy can artificially impose land scarcity and incentivize agricultural actors to intensify their production. Second, our findings show that environmental policies that aim to decrease deforestation are not viable in the long run without increased investment in land. Indeed, pasture degradation without increased investment in land implies that − sooner or later − at least a portion of landowners will produce at unsustainable density levels and as such, will increase deforestation or leave the industry altogether. This means that policymakers should promote training and oversight to ensure that intensification spurred by land use policies is both safe and sustainable, particularly with populations that are unfamiliar with non-organic pesticides and fertilizers. Third, inclusion of all slaughterhouses in the zero-deforestation policy would bring about greater impact both to reduce deforestation and to increase productivity and investment. Fourth, public- and private-led environmental policies, particularly for developing countries, can complement one another by targeting producers with different characteristics.

References

Alix-Garcia, J. and Gibbs, H. K. (2017). Forest conservation effects of Brazil's zero deforestation agreements undermined by leakage. *Global Environmental Change*, 47:201–217.

Alix-Garcia, J. M., Sims, K. R. E., Orozco-olvera, V. H., and Costica, L. E. (2018). Payments for environmental services supported social capital while increasing land management. *Proceedings of the National Academy of Sciences*.

Angelsen, A. (2010). Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the National Academy of Sciences of the United States of America*, 107(46):19639–19644.

Aragón, F. M. and Rud, J. P. (2016). Polluting Industries and Agricultural Productivity: Evidence from Mining in Ghana. *Economic Journal*, 126(597):1980–2011.

Archsmith, J., Heyes, A., and Saberian, S. (2018). Air Quality and Error Quantity: Pollution and Performance in a High-Skilled, Quality-Focused Occupation. *Journal of the Association of Environmental and Resource Economists*, 5(4).

Arima, E. Y., Barreto, P., Araújo, E., and Soares-Filho, B. (2014). Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. *Land Use Policy*, 41:465–473.

Ashraf, N., Jack, B. K., and Kamenica, E. (2013). Information and subsidies: Complements or substitutes? *Journal of Economic Behavior and Organization*, 88:133–139.

Assunção, J., Gandour, C., and Rocha, R. (2015). Deforestation slowdown in the Brazilian Amazon: prices or policies? *Environment and Development Economics*, pages 1–5.

Assunção, J., Gandour, C., Rocha, R., and Rocha, R. (2013). Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon. *Climate Policy Initiative*, (January):50.

Assunção, J., Lipscomb, M., Mobarak, A. M., and Szerman, D. (2017). Agricultural Productivity and Deforestation in Brazil. *Working Paper*.

Assunção, J., McMillan, R., Murphy, J., and Souza-Rodrigues, E. (2019). Optimal Environmental Targeting in the Amazon Rainforest. *NBER Working Papers 25636*, page 85.

Assunção, J. and Rocha, R. (2014). Getting Greener by Going Black: The Priority Municipalities in Brazil. Technical Paper. *Climate Policy Initiative, PUC-Rio*, (August):18.

Autor, D. H. and Duggan, M. G. (2003). The rise in the disability rolls and the deline in unemployment. *Quarterly Journal of Economics*, (February):157–205.

Azevedo, A. A., Rajão, R., Costa, M. A., Stabile, M. C. C., Macedo, M. N., dos Reis, T. N. P., Alencar, A., Soares-Filho, B. S., and Pacheco, R. (2017). Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proceedings of the National Academy of Sciences*, page 201604768.

Banco do Brasil (2019). Rural Credit Manual [Manual de Crédito Rural]. Technical report, Banco do Brasil, Brasilia.

Berman, E. and Bui, L. T. M. (2001). Environmental Regulation and Productivity: Evidence from Oil Refineries. *The Review of Economics and Statistics*, 83(3):498–510.

Borlaug, N. (2007). Feeding a Hungry World. *Science*, 318(October):359–359.

Burgess, R., Costa, F. J. M., and Olken, B. A. (2018). Wilderness Conservation and the Reach of the State: Evidence from National Borders in the Amazon. *NBER Working Paper*.

Carlson, K. M., Heilmayr, R., Gibbs, H. K., Noojipady, P., Burns, D. N., Morton, D. C., Walker, N. F., Paoli, G. D., and Kremen, C. (2017). Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proceedings of the National Academy of Sciences*, 115(1):201704728.

Cisneros, E., Zhou, S. L., and Börner, J. (2015). Naming and shaming for conservation: Evidence from the Brazilian Amazon. *PLoS ONE*, 10(9):1–24.

Cohn, A. S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., and Obersteiner, M. (2014). Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, 111(20).

de Castro, E. R. and Teixeira, E. C. (2012). Rural credit and agricultural supply in Brazil. *Agricultural Economics*, 43(3):293–302.

Deserranno, E., Nansamba, A., and Qian, N. (2019). Aid Crowd-Out: The Effect of NGOs on Government-Provided Public Services. *Working Paper*.

Ermgassen, E. K. H. J., Pereira de Alcântara, M., Balmford, A., Barioni, L., Beduschi Neto, F., Bettarello, M. M. F., de Brito, G., Carrero, G. C., de A S Florence, E., Garcia, E., Trevisan Gonçalves, E., Trajano da Luz, C., Mallman, G. M., Strassburg, B. N. B., Valentim, J. F., and Latawiec, A.

(2018). Results from On-The-Ground Efforts to Promote Sustainable Cattle Ranching in the Brazilian Amazon. *Sustainability*, 10(1301).

Fearnside, P. (1989). Ocupação Humana de Rondônia: Impactos, Limites e Planejamento. Technical report, Conselho Nacional de Desenvolcimento Científico e Tecnológico.

Fearnside, P. M. and Barbosa, R. I. (1998). Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management*, 108(1-2):147–166.

Garrett, R., Levy, S., Carlson, K., Gardner, T., Godar, J., Clapp, J., Dauvergne, P., Heilmayr, R., le Polain de Waroux, Y., Ayre, B., Barr, R., Døvre, B., Gibbs, H., Hall, S., Lake, S., Milder, J., Rausch, L., Rivero, R., Rueda, X., Sarsfield, R., Soares-Filho, B., and Villoria, N. (2019). Criteria for effective zero-deforestation commitments. *Global Environmental Change*, 54:135–147.

Gibbs, H., Moffette, F., Munger, J., Vale, P., Rausch, L., L'Roe, J., Barreto, P., Amaral, T., Hall, S., and Walker, N. (2019). Impacts of Zero-Deforestation Cattle Agreements in the Brazilian Amazon Limited by Inconsistent and Evasive Behavior. *Environmental Research Letters*, (August).

Gibbs, H. K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T., and Walker, N. F. (2016). Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? *Conservation Letters*, 9(1):32–42.

Gil, J. D. B., Garrett, R. D., Rotz, A., Daioglou, V., Valentim, J., and Gabrielle, F. (2018). Tradeoffs in the quest for climate smart agricultural intensification in Mato Grosso , Brazil. *Environmental Research Letters*, 13(6).

Godar, J., Gardner, T. A., Tizado, E. J., and Pacheco, P. (2015). Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, 112(23):201508418.

Greenpeace (2009). Minimum criteria for industrial scale cattle operations in the Brazilian Amazon Biome. `http://www.greenpeace.org/international/en/media-center/reports/minimum-criteria-for-i/`. (accessed on 2017-12-20).

Hanna, R. and Oliva, P. (2015). The effect of pollution on labor supply: Evidence from a natural experiment in Mexico City. *Journal of Public Economics*, 122:68–79.

Heilmayr, R. and Lambin, E. F. (2016). Impacts of nonstate, market-driven governance on Chilean forests. *Proceedings of the National Academy of Sciences*, 113(11):2910–2915.

Heilmayr, R., Rausch, L., Munger, J., and Gibbs, H. (2019). Avoided deforestation from the Soy Moratorium. *Nature Sustainability*.

IBGE (2007). Censo Agropecuario 2006: Segunda Apuração. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9827-censo-agropecuario.html?edicao=9830t=resultados.

IBGE (2017). Produção Pecuária Municipal. `https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9107-producao-da-pecuaria-municipal.html?=&t=publicacoes`. Accessed: 2018-12-15.

IBGE (2019). Censo Agropecuario 2017: Resultados Preliminarios. https://censos.ibge.gov.br/agro/2017/templates/censo_agro/resultadosagro/index.html.

Inderbitzin, L., Staubli, S., and Zweimüller, J. (2016). Extended unemployment benefits and early retirement: Program complementarity and program substitution. *American Economic Journal: Economic Policy*, 8(1):253–288.

INPE (2019). Projeto PRODES – monitoramento da floresta amazônica brasileira por satélite. `http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes`.

Jaime, M. M., Coria, J., and Liu, X. (2016). Interactions between CAP Agricultural and Agri-Environmental Subsidies and Their Effects on the Uptake of Organic Farming. *American Journal of Agricultural Economics*, 98(4):1114–1145.

Kaimowitz, D. and Angelsen, A. (2008). Will Livestock Intensification Help Save Latin America's Tropical Forests? *Journal of Sustainable Forestry*, 27(1-2):6–24.

Koch, N., zu Ermgassen, E., Wehkamp, J., Oliveira Filho, F., and Schwerhoff, G. (2019). Agricultural Productivity and Forest Conservation: Evidence from the Brazilian Amazon. *American Journal of Agricultural Economics*, pages 1–22.

Lambin, E. F., Gibbs, H. K., Heilmayr, R., Carlson, K. M., Fleck, L. C., Garrett, R. D., Waroux, P. D., Mcdermott, C. L., Mclaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L. L., and Streck, C. (2018). The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change*, 8(February):109–116.

Lambin, E. F., Meyfroidt, P., Rueda, X., Blackman, A., Börner, J., Cerutti, P. O., Dietsch, T., Jungmann, L., Lamarque, P., Lister, J., Walker, N. F., and Wunder, S. (2014). Effectiveness and synergies of policy instruments for land use governance in tropical regions. *Global Environmental Change*, 28(1):129–140.

le Polain de Waroux, Y., Garrett, R. D., Graesser, J., Nolte, C., White, C., and Lambin, E. F. (2019). The Restructuring of South American Soy and Beef Production and Trade Under Changing Environmental Regulations. *World Development*, 121:188–202.

Nepstad, D., Mcgrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., Digiano, M., Shimada, J., Seroa, R., Armijo, E., Castello, L., Brando, P., Hansen, M. C., Mcgrath-horn, M., Carvalho, O., and Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, 344(6188):7.

Pailler, S. (2018). Re-election incentives and deforestation cycles in the Brazilian. *Journal of Environmental Economics and Management*, 88:345–365.

Phalan, B., Green, R. E., Dicks, L. V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B. B. N., Williams, D. R., Ermgassen, E. K. H. J. z., and Balmford, A. (2016). How can higher-yield farming help to spare nature? *Science*, 351(6272):450–451.

Pless, J. (2019). Are "Complementary Policies" Substitutes? Evidence from R&D Subsidies in the UK.

Presidéncia da República, C. C. (2009). Plano de Ação para a Prevenção e o Controle do Desmatamento na Amazônia Legal. Technical report.

Rausch, L. L., Gibbs, H. K., Schelly, I., Brandão, A., Morton, D. C., Filho, A. C., Strassburg, B., Walker, N., Noojipady, P., Barreto, P., and Meyer, D. (2019). Soy Expansion in Brazil's Cerrado. *Conservation Letters*.

Sims, K. R. and Alix-Garcia, J. M. (2017). Parks versus PES: Evaluating direct and incentive-based land conservation in Mexico. *Journal of Environmental Economics and Management*, 86:8–28.

Soares-filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., and Alencar, A. (2014). Cracking Brazil's Forest Code. *Science*, 344(6182):363–364.

Strassburg, B. B., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., and Assad, E. D. (2014). When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, 28(1):84–97.

USDA Foreign Agricultural Service (2019). Livestock and Poultry: World Markets and Trade. `https://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf`.

Vale, P. (2015). *Land Use Intensification in the Amazon: Revisiting Theories of Cattle, Deforestation and Development in Frontier Settlements*. Phd thesis, The London School of Economics and Political Science.

Villoria, N. B., Byerlee, D., and Stevenson, J. (2014). The effects of agricultural technological progress on deforestation: What do we really know? *Applied Economic Perspectives and Policy*, 36(2):211–237.

Walker, N. F., Patel, S. A., and Kalif, K. A. (2013). From Amazon pasture to the high street: Deforestation and the brazilian cattle product supply chain. *Tropical Conservation Science*.

Yang, C.-H., Tseng, Y.-H., and Chen, C.-P. (2012). Environmental regulations, induced R&D, and productivity: Evidence from Taiwan's manufacturing industries. *Resource and Energy Economics*, 34:514–532.

A Theoretical model with capital transfer

Here we present our theoretical model where the inputs of the first period (M_1) are fully available in the second period, while our main model presented the case where the inputs of the first period were completely depleted in the second period. Consumable inputs would correspond to the case with 100% deterioration, while inputs presented in this appendix represent an extreme case where infrastructure projects and capital would not suffer any depletion. We show that the conclusions of the model are robust to this extreme scenario, and therefore hold for intermediate levels of capital transfer from the first to the second period.

In the second period, the rancher maximizes:

$$\begin{aligned} Max_{\{H_2,M_2\}} \quad & f((1-\alpha)H_2,M_1+M_2)-rM_2-cH_2 \\ s.t. \quad & H_1+H_2<A. \end{aligned} \tag{17}$$

The FOC for land requires:

$$\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial H_2}=c+\lambda \tag{18}$$

and the FOC for inputs requires:

$$\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial M_2}=r \tag{19}$$

Clearly, the rancher must set $H_2>0$ or $M_2>0$ to satisfy the FOC. The rancher will produce such that

$$\frac{\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial H_2}}{\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial M_2}}=\frac{c+\lambda}{r}. \tag{20}$$

A.1 Policy 1: Fines for deforestation

The maximization problem with fines for deforestation becomes:

$$\begin{aligned} Max_{\{H_2,M_2\}} \quad & f((1-\alpha)H_1+H_2,M_1+M_2)-rM_2-cH_2-P(H_2) \\ s.t. \quad & H_1+H_2<A, \end{aligned} \tag{21}$$

and equation 6 now becomes:

$$\frac{\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial H_2}}{\frac{\partial f((1-\alpha)H_1+H_2,M_1+M_2)}{\partial M_2}} = \frac{c+\lambda+P'(H_2)}{r}. \tag{22}$$

Once again, the rancher will choose less pasture, H_2 and more inputs, M_2, than they would in the absence of the policy. This leads to a higher ratio $\frac{M}{H}$ than in the absence of the policy, as ranchers choose to intensify.

A.2 Policy 2: Market exclusion following deforestation

The rancher now solves:

$$\begin{aligned} Max_{\{H_2, M_1+M_2\}} \quad & (1-\mathbb{1}\{H_2>0\}\beta)f((1-\alpha)H_1+H_2,M_1+M_2) - rM_2 - cH_2 \\ s.t. \quad & H_1+H_2<A. \end{aligned} \tag{23}$$

The rancher maximizes their profit with and without clearing.

- **Case 1: Intensification (N)** ($H_2 = 0$)

  Now land is fixed at H_1 and the ranchers solves:

  $$Max_{M_2} \quad f((1-\alpha)H_1, M_1+M_2) - rM_2. \tag{24}$$

  In this case, the rancher maximizes based on one FOC:

  $$\frac{\partial f((1-\alpha)H_1, M_1+M_2)}{\partial M_2} = r. \tag{25}$$

  Thus, the rancher chooses $M_2 > 0$ to compensate for the soil degradation, and both M_2 and $\frac{M}{H}$ are higher than they would be in the absence of the policy.

- **Case 2: Extensification (X)** ($D > 0$)

  The rancher maximizes:

  $$\begin{aligned} Max_{\{H_2, M_2\}} \quad & (1-\beta)f((1-\alpha)H_1+H_2, M_1+M_2) - rM_2 - cH_2 \\ s.t. \quad & H_1+H_2<A. \end{aligned} \tag{26}$$

Again, the ratio of the FOC is identical to equation 20, and the ratio $\frac{M}{H}$ is the same as it would be in the absence of the policy.

We have shown that the fundamental conclusions of the model are unchanged by the assumption of how inputs transfer between periods. In policy 1, ranchers choose a lower level of deforestation and instead intensify, increasing $\frac{M}{H}$. In policy 2, ranchers make a discontinuous decision either to not clear at all or continue producing at the same level of intensity. We conclude that the model applies to the intermediate setting where inputs transfer between periods but degrade in a manner similar to pasture.

B Summary statistics

Table 8: Summary statistics (means and standard deviations)

	Amazon sample		Falsification sample	
	mean	s.d.	mean	s.d.
Treatments				
Exposure to the G4 (2010)	0.33	(0.26)	0.32	(0.23)
Blacklist (2008)	0.15	(0.36)	0.00	(0.00)
Outcomes				
Productivity (2007)	1.31	(0.69)	1.85	(5.06)
Productivity (2016)	1.54	(0.63)	1.67	(2.30)
Prod. relative to capacity (%) (2007)	37.74	(23.19)	43.69	(77.92)
Prod. relative to capacity (%) (2016)	43.82	(20.03)	42.92	(42.09)
Credit/ha of pasture (R$) (2007)	76.36	(54.23)	335.95	(996.88)
Credit/ha of pasture (R$) (2016)	166.73	(178.37)	709.98	(3267.80)
Nbr of contracts (2007)	300.86	(529.78)	172.29	(255.19)
Nbr of contracts (2016)	316.14	(332.71)	203.65	(300.16)
Clearing/ha (%) (2007)	0.010	(0.014)	0.003	(0.004)
Clearing/ha (%) (2016)	0.007	(0.007)	0.006	(0.008)
Other variables				
Properties $\geq$ 500 ha (%) (2006)	0.08	(0.09)	0.06	(0.10)
Natural vegetation (%)	0.55	(0.26)	0.32	(0.26)
Protected area (%) (2007)	0.14	(0.23)	0.05	(0.16)
Sustainable cattle per ha	3.62	(0.54)	3.82	(1.31)
Head of cattle (2007)	183202	(174593)	63127	(113442)
Pasture area (ha) (2007)	162826	(158292)	51545	(88372)
Municipality area (kha)	690937	(1386179)	125734	(285552)
Observations	242		1292	

Note. Unit of observation is the municipality. Amazon sample consists of all municipalities that have ever had a G4 slaughterhouse within 100 km and the MPs that are adjacent to this sample. The falsification sample consists of all municipalities that have ever had a G4 slaughterhouse within 100 km outside of the Amazon biome.

C Credit for operations and investment

Table 9: Estimated effect of the G4 and the MPs on credit for operations and for investment

	Credit for operation				Credit for investment			
	Value/ha of pasture		Nbr contracts		Value/ha of pasture		Nbr contracts	
G4	19.524**	20.700***	40.571**	41.037**	21.221	23.493*	82.000***	85.703***
	(7.555)	(7.236)	(17.826)	(17.972)	(12.752)	(13.024)	(28.585)	(29.326)
MP	9.430	10.104	12.304	13.844	0.171	-1.165	15.358	8.266
	(8.616)	(8.413)	(12.571)	(12.565)	(7.172)	(7.460)	(53.105)	(54.115)
G4 × MP	-16.729*	-18.149*	-53.548***	-54.283***	10.905	8.519	-282.546*	-285.770*
	(9.276)	(8.861)	(18.522)	(18.483)	(17.695)	(17.534)	(148.941)	(150.889)
Lincom								
G4 + MP	12.225	12.655*	-0.673	0.598	32.297*	30.847*	-185.188	-191.802
	(7.299)	(6.642)	(17.058)	(16.611)	(17.556)	(17.798)	(126.277)	(128.774)
Observations	3,097	3,097	3,097	3,097	3,097	3,097	3,097	3,097
Pre-period mean (G4-only)	39.3	39.3	42.4	42.4	91.1	91.1	152.7	152.7
Pre-period mean (MP-only)	28.1	28.1	38.1	38.1	55.0	55.0	79.8	79.8
Pre-period mean (G4-MP)	23.0	23.0	30.8	30.8	116.6	116.6	476.8	476.8
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

D Robustness of the falsification test

Table 10: Falsification test – Estimated effect of the G4 outside the Amazon on cattle productivity and credit without biome specific flexible time trends

	Productivity				Credit			
	Head/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4 - out of the Amazon	-0.236	-0.240	-3.553	-3.593	-204.644	-211.864	91.039***	89.262***
	(0.165)	(0.168)	(2.787)	(2.846)	(229.314)	(235.140)	(31.367)	(31.328)
Observations	16,751	16,751	16,751	16,751	16,537	16,537	16,537	16,537
Pre-period mean (G4)	1.8	1.8	43.7	43.7	335.9	335.9	172.3	172.3
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. * p< 0.10, ** p<0.05, *** p<0.01.

E Robustness by excluding the MP municipalities that never been within the reach of a G4

Table 11: Estimated effect of the G4 and the MPs on cattle productivity and credit

	Productivity				Credit			
	Heads/ha of pasture		Percent of capacity		Value/ha of pasture		Nbr contracts	
G4	0.162***	0.161***	4.791**	4.744**	63.210**	64.621**	115.323***	121.271***
	(0.056)	(0.056)	(1.744)	(1.742)	(23.459)	(23.275)	(32.081)	(32.431)
MP	0.101	0.082	2.441	1.926	0.450	3.195	-18.215	-29.470
	(0.062)	(0.059)	(1.805)	(1.761)	(12.427)	(11.799)	(68.366)	(70.757)
G4 × MP	-0.039	-0.031	-0.872	-0.619	-52.482**	-55.408***	-245.064	-249.145
	(0.055)	(0.054)	(2.023)	(1.987)	(18.976)	(18.836)	(162.321)	(164.084)
Lincom								
G4 + MP	0.223**	0.211**	6.361**	6.050**	11.178	12.408	-147.955	-157.344
	(0.087)	(0.084)	(2.652)	(2.582)	(20.794)	(19.858)	(128.261)	(131.166)
Observations	3,040	3,040	3,040	3,040	2,993	2,993	2,993	2,993
Pre-period mean (G4-only)	1.4	1.4	39.9	39.9	81.7	81.7	243.8	243.8
Pre-period mean (MP-only)	0.9	0.9	27.0	27.0	66.2	66.2	134.8	134.8
Pre-period mean (G4-MP)	1.0	1.0	29.7	29.7	53.9	53.9	593.5	593.5
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

F Results of clearing in the Amazon

Table 12: Estimated effect of the G4 and the MPs on clearing for pasture

	2004-16				2004-12			
	Clearing (kha)		Clearing/ha		Clearing (kha)		Clearing/ha	
G4	-0.212	-0.185	0.002*	0.002*	-0.891	-0.591	0.004	0.004
	(0.839)	(0.867)	(0.001)	(0.001)	(0.940)	(0.910)	(0.002)	(0.003)
MP	-3.733**	-3.385*	0.000	-0.000	-5.565***	-5.146**	-0.000	-0.001
	(1.732)	(1.772)	(0.001)	(0.001)	(1.960)	(2.021)	(0.002)	(0.002)
G4 × MP	-0.339	-0.415	-0.001	-0.000	-0.483	-0.779	-0.002	-0.002
	(1.586)	(1.637)	(0.001)	(0.002)	(2.459)	(2.472)	(0.002)	(0.003)
Lincom								
G4 + MP	-4.285*	-3.986	0.002	0.002	-6.940***	-6.516***	0.002	0.001
	(2.349)	(2.435)	(0.002)	(0.002)	(2.149)	(2.247)	(0.003)	(0.003)
Observations	3,081	3,081	3,081	3,081	2,133	2,133	2,133	2,133
Pre-period mean (G4-only)	3.116	3.116	0.010	0.010	3.116	3.116	0.010	0.010
Pre-period mean (MP-only)	5.785	5.785	0.008	0.008	5.785	5.785	0.008	0.008
Pre-period mean (G4-MP)	14.205	14.205	0.009	0.009	14.205	14.205	0.009	0.009
Active SIFs		X		X		X		X
Protected areas		X		X		X		X
Municipality FE	X	X	X	X	X	X	X	X
Time FE	X	X	X	X	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.

G Additional outcomes

Table 13: Estimated effect of the G4 and the MPs on pasture area and head of cattle

	Pasture/ha		Head/ha	
G4	-0.006	-0.006	0.041**	0.040**
	(0.012)	(0.012)	(0.016)	(0.016)
MP	0.010	0.009	0.031*	0.031*
	(0.009)	(0.009)	(0.015)	(0.016)
G4 × MP	0.005	0.005	-0.017	-0.016
	(0.011)	(0.011)	(0.027)	(0.027)
Lincom				
G4 + MP	0.009	0.008	0.055**	0.055**
	(0.015)	(0.015)	(0.023)	(0.024)
Observations	3,146	3,146	3,144	3,144
Pre-period mean (G4-only)	0.5	0.5	0.6	0.6
Pre-period mean (MP-only)	0.2	0.2	0.2	0.2
Pre-period mean (G4-MP)	0.3	0.3	0.3	0.3
Active SIFs		X		X
Protected areas		X		X
Municipality FE	X	X	X	X
Time FE	X	X	X	X

Note. Unit of observation is the municipality. Robust standard errors are in parentheses and are clustered at the microregion level. Pre-period means are calculated for 2007. G4-only, MP-only and G4-MP are mutually exclusive categories. * p< 0.10, ** p<0.05, *** p<0.01.